THE EFFECTS OF FLOODS AND SOCKEYE SALMON ON STREAMBED MORPHOLOGY

by

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Abstract

Streambed changes resulting from floods and spawning activity of sockeye salmon were monitored in two gravel bed streams in Stuart-Takla Experimental Watersheds of the Upper Fraser River basin, British Columbia, Canada. The streams have a forced pool-riffle morphology, and are utilized yearly by 7,000 to 10,000 sockeye salmon for spawning. Streambed mapping was performed before and after nival floods, summer floods and sockeye salmon spawning events in 1996 and 1997.

Flood transport moves gravel out of pools, increases gravel bar heights, creates scour holes, and establishes a distinct thalweg. Sockeye spawning, which follows the floods, removes gravel from the edges and surface of the bars, and fills in the pools, scour holes and thalweg. The stream morphology is thus altered in opposing fashion by two different processes. It was found that the cut and fill volumes are similar in magnitude but that the two processes affect the stream in a very different manner.

Chapter 1

Introduction

The relationship between sediment transport rate and streamflow conditions has been investigated over the last two centuries to in an attempt to predict bedload movement. Investigations evaluating the patterns between sedimentary factors (such as grain size distribution and shape, protrusion of the grain into the flow, imbrication and pebble clusters) and flow variables (such as average shear stress, drag force and roughness) demonstrate the non-linear relationship between sedimentary and flow conditions. In perennial streams, both sets of factors play a major role in controlling sediment transport and hence enhance the stability of alluvial sediments.

Along with streamflow, salmon activity is another important process by which channel bed sediments are mobilized. Salmon excavate sediments and through this process partially destroy the surface structure, making finer sediment from the subsurface available for transport. During reproduction, the female sockeye salmon excavates a bowl-shaped nest (termed redd) on the streambed to provide an area to deposit eggs. Upon completion of the redd, the female sockeye salmon releases her eggs into the nest. The male sockeye salmon immediately approaches the center of the nest, fertilizes the eggs and departs. The female returns to bury her fertilized eggs using the upstream gravels further altering the streambed.

In some respects, floods are of greater significance than salmon activity in terms of the magnitude of sediment transport. However, salmon spawning can play a major role through both vertical mixing and limiting the development of river bed surface armoring. Many studies have described the redd construction process and/or measured and quantified the gravel sizes associated with redd construction (Soulsby et al. 2001). As well a few studies (Gottesfeld 1998, Rennie and Millar 2000) have evaluated the effects and the interaction of these two processes on the streambed in order to compare the patterns and relative magnitude of bed load transport.

The objectives of this study were to (1) delineate the pattern of change on the streambed associated with high flow (flood) events, (2) delineate the pattern of change on the streambed associated with salmon spawning (bioturbation), (3) compare the magnitude (volume) and pattern of change associated with both processes.

The approach used to characterize the channel bed surface involved conducting high-density topographic surveys following floods and spawning events. The topographic data were used to develop digital elevation models that delineate fine-scale topographic changes resulting from both the floods and spawning activities.

To facilitate the interpretation of the study results, a review of the literature will provide an explanation of how the streambed load is mobilized and transported in fluvial systems (Section 2.2), a description of bed load measurement techniques typically used (Section 2.3) and a presentation of how the sockeye salmon disturb the streambed during the spawning process (Section 2.4).

The observed stream changes are then presented for both the flood and the spawning processes (Section 4.1), quantified (Section 4.2) and spatial patterns of bed load transfers presented for comparison (Section 4.3). A discussion on how the magnitude and pattern of bed load transport compare and contrast is presented. Finally, the effects of sockeye salmon spawning on the streambed are addressed in terms of how this study increases the understanding of streambed mobilization (Section 5).

Chapter Two

Literature Review

2.1 Introduction

Although substantial research has been conducted on the prediction of sediment transport rates and processes associated with flood events, a complete sediment transport model which describes both the flow of water and the movement of sediments has yet to be produced. Conventional techniques to calculate sediment transport in large rivers are not appropriate for small streams for a variety of reasons, which include an increased supply of material (both organic and inorganic) from external sources (slopes and banks). In forested streams, Large Woody Debris (LWD) constitutes an integral part both of channel morphology and the material transported by streams (Bilby 1981). It also acts as a controlling structure to the downstream progress of clastic material (Hogan et al. 1998a, Hogan et al. 1998b).

The total sediment load in a stream is typically divided into two categories:

Suspended load – particles that generally move as part of the water column and are supported by buoyancy, and

Bedload – particles that move in contact with the streambed (Bagnold 1968).

The division between suspended load and bed load depends on the energy of the stream and sediment sources (Church 1992). The two modes of transport are divided at approximately the 0.064 mm to 2.0 mm particle size range, which corresponds to the sand fraction of the grains-size classification (Knighton 1998, Simon and Simons 1987).

A somewhat different division provides insight into channel formation and stability. *Bed material* is the coarser material that is apt to be deposited on and form the channel bed and banks whereas *wash material* (fine material supplied from the slopes) is the portion of the fine material that moves through the reach without being deposited. In headwater streams, there is a strong similarity between bed material and bedload. Due to this similarity, I will principally consider the literature regarding bedload. Specific topics will include:

1) Initiation of sediment movement.
2) Models and modes (phases) of sediment transport in rivers.
3) Measurement of bed material transport.

2.2 Initiation of Bedload Transport

The accepted paradigm to predict sediment transport in stream channels is to assume that there is an unlimited supply of bed material in the channel and that movement is related to the force imposed by the water flow (Naden 1988). Before any sediment entrainment can occur, the flow must exceed a threshold of motion where the dynamic flow force exceeds the static force of the streambed.

Many sediment transport theories are based on this concept of critical flow conditions in non-cohesive bed materials streams (e.g. Wilcock 1992). However, for heterogeneous sediment, there is no single flow threshold above which all clasts of the same size will move (Wilcock and McArdell 1993; 1997). Figure 1 is a representation of the interrelationship between the flow hydraulics, the materials, sediment transport and the channel. Other flow charts have been presented (Lane et al. 1995, Knighton 1998) and in principle are very similar to Figure 1, which demonstrates the complexities of natural fluvial systems and the difficulty in predicting sediment transport in rivers.

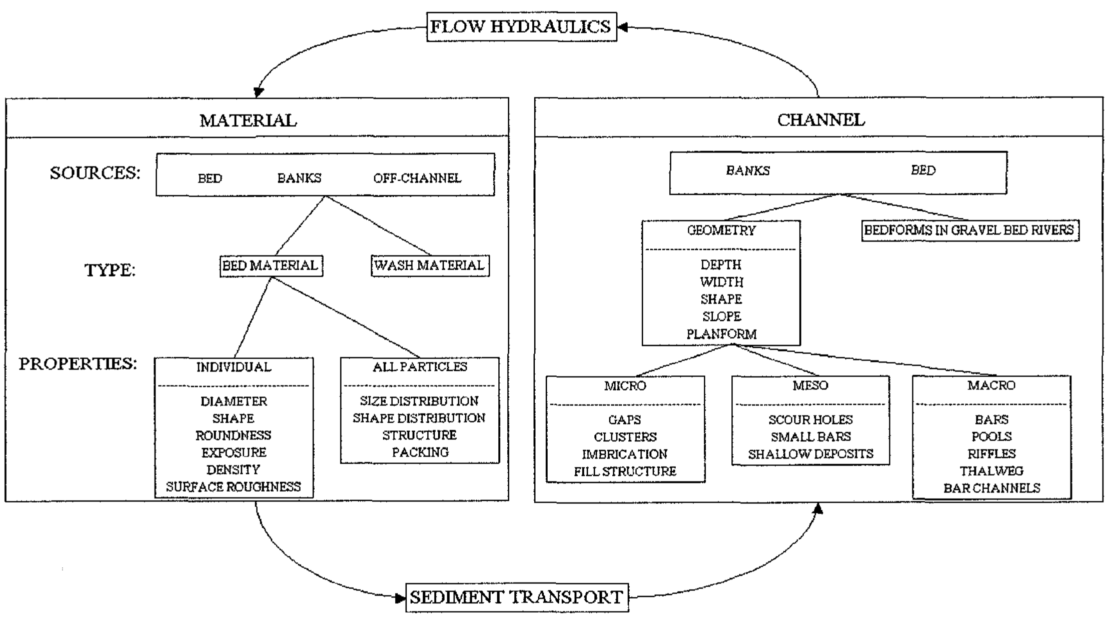

Figure 1: Channel-Flow-Material-Transport Relationship (modified from Hassan and Church 1992)

Shields (1936) investigated the shear stress needed to initiate movement of a uniform grain size material. He determined that for particles larger than 5 mm in diameter, the scaled shear stress (dimensionless mobility number) on hydraulically rough beds rapidly attains a constant value of 0.056. This approach fails to adequately cope with the variability of flow conditions near the streambed and the streambed material characteristics. As a result, Shields' equation appears to predict sediment transport in fine or well-sorted sediments, while its application to poorly sorted sediments, typical of natural channels, has proven to be difficult. In poorly sorted sediment, the larger grains may be transported more readily, resulting from higher exposure on the streambed (Baker and Ritter 1975, Bagnold 1977, Simons and Senturk 1977, Wiberg and Smith 1987). Komar and Li, 1988 suggest that these grains have a lower pivotal point as compared to the smaller grain sizes in the matrix. Correspondingly, the larger exposed grain size may act as a barrier to the smaller grain size, sheltering them from movement (Einstein 1950, Parker and Klingerman 1982). For poorly sorted sediments, a range of threshold mobility numbers (scaled shear stress) has been reported from 0.01 to more than 0.10 (Church 1978, Buffington and Montgomery 1997, Church et al. 1998, Hassan and Church 2000). Baker and Ritter (1975) suggest that the total boundary shear stress (τ_o) related to the initial motion of large gravel particles may be less than that predicted by Shields' equation. The wide range of sediment transport values predicted using Shields' equation in natural streambeds has been explained by surface structures, pebble clusters, armouring, and over exposure in the case of large material (e.g. Church and Hassan 1998, Hassan and Church 2000). These factors which appear to impede good prediction of sediment transport via Shields' equation are some of the major bed characteristics that control channel stability. A detailed discussion of these factors is provided below.

2.2.1 Streambed surface variability

The mobilization of the bedload by the hydraulic forces acting on it is further complicated by the effects of interlocking particles in the streambed (Billi 1988). Several other channel surface conditions such as relative protrusion of the individual particles (Carson and Griffiths 1985, Fenton and Abbott 1977), pavement structure imbrications, and packing of the substrate (Laronne and Carson 1976) also serve to confound predictions of bed mobilization. Two surface streambed conditions I will concentrate on include the following:

pebble clusters distributed over the streambed (Hassan and Reid 1990, Reid et al. 1992),

bed armouring (Lisle and Madej 1992, Lamberti and Paris. 1992)

because they are both significant in the bed structure and stability of salmon bearing streams.

2.2.2 Pebble clusters

Pebble clusters are generally described as a grouping of pebbles which has a large particle at its central core which modifies flows resulting in the deposition of smaller particles on the upstream (stoss) and downstream (wake) of the obstruction. To evaluate the effects of streambed pebble clusters on particle entrainment, Hassan and Reid (1990) conducted a series of flume experiments. The study consisted of introducing controlled pebble clusters on the streambed under steady flow conditions and evaluating the effects of both flow resistance and bed load flux. They found that pebble clusters initially increased and then decreased flow resistance resulting in a delay in the entrainment threshold. Under rising water stage, both Bathhurst (1982) and Carling (1983) have demonstrated substantial reductions in gross flow resistance in gravel bed rivers due to pebble clusters. This leads to the conclusion that the relative impact of microform roughness on particle entrainment velocities could vary considerably. Similar studies conducted by Fenton and Abbott (1977) and Andrews (1983) demonstrate that the critical shear stress for particles surrounded by larger particles is significantly greater than that of particles surrounded by smaller particles. Billi (1988) evaluated the behavior of cluster bedforms on the Farm River (central Italy), and found that they could be playing an important role in maintaining a constant grain size distribution on the streambed. He proposed that this was due to the effect of smaller particles 'hiding' in the wake of the obstacles (pebble clusters). Billi (1988) further hypothesized that pebble clusters could favor streambed armouring or help in maintaining a constant size distribution of bedload since pebble clusters are made up by particles of all sizes available to the stream.

2.2.3 Streambed armouring

The portions of the stream experiencing the highest flow are typically described as being armoured which implies an interlocked coarse bed surface. The static armour surface forms when a heterogeneous mixture of surface streambed gravels is subjected to a flow sufficient to transport most of the finer materials leaving a surface layer that is two to three time coarser than the underlying material (Parker et al. 1982, Andrews and Parker 1987, Sutherland 1987).

The interlocking effect of the coarser material, also known as pavement imbrication, in the armour layer restricts the movement of bed load sediment during low flow periods. During periods of high flow, such as nival and summer floods, the integrity of the armour layer decreases until it breaks up. During periods of high flow, the armour and sub-armour layers are fully mobilized, and all the materials are entrained (full mobilization), until such time as the flow decreases and the armour layer is once again re-established (Parker et al. 1982, Andrews 1983, Gomez 1983).

This condition of full mobilization has been termed 'equal mobility', and has been the subject of much interest and debate (Church et al. 1991, Komar and Shih 1992). Wilcock and Southard (1989) state that for equal mobility to be a general phenomenon, it would be necessary for all particle sizes to have a common threshold of motion. Church et al. (1991) conducted sediment trap studies during a nival flood event and concluded that 'equal mobility' of fine sediments appeared, at best, to be a statistical phenomenon that held for a limited range of grain sizes. In more recent paper, Church and Hassan (2002) showed that full mobility exists for particle sizes up to 16 mm in diameter; larger particles are only partially mobile (e.g. not all particles of the large size fraction moved). It follows, then, that the development of an armour layer within the streambed, providing an imbricate pavement structure, leads to near equal mobility of bed material during large mobilization events. This is likely to occur once every few years as shown in Hassan and Church (2001) Harris Creek study. It appears that the concept of initiation of bedload transport in streams is still largely an open question in fluvial morphology that needs to be studied further.

2.2.4 Models and Modes (phases) of Sediment Transport in Rivers

Field studies of sediment transport in rivers have identified two-phase (Emmett 1976, Jackson and Beschta 1982, Klingeman and Emmett 1982, Andrews 1983) or three-phase (Ashworth and Ferguson 1989, Warburton 1992) modes of transport in gravel bed rivers. Phase I of bed load transport consists of sand-sized material moving over a stable streambed during low flows. Phase II occurs at moderate flows with size-selective entrainment and transport of local material, and Phase III transport occurs when most sizes in the bed are mobile. Phase III occurs only during the highest flow conditions, which is effectively described as equal mobility (see Section 2.2.3).

These three phases of sediment transport can be related to the flood hydrograph. During the rising limb of the flood hydrograph Phase I occur, entraining sand-sized sediments. As the streamflows increase, selective entrainment of the streambed occurs, representing Phase II. Phase III occurs during periods of relatively high flows and is likely to occur only once every few years.

A number of studies have examined the short-term variation in sediment transport at different stages of the flood hydrograph. The bed load transport rate was found to peak with or after the maximum discharge (Paustan and Beschta 1979, Moog and Whiting 1998). In addition, highly unsteady flow can increase sediment transport rates (Phillips and Sutherland 1989). Variation in sediment transport at equal discharge is called hysteresis and many of these have been described in field studies (Moog and Whiting, 1998, Hassan and Church 2001). Such variation in sediment transport introduces additional complexity to sediment transport in rivers, and renders the physical model of limited use. A large number of mathematical, deterministic and stochastic models, via hydraulically based functions, have been developed to predict sediment transport. These bed load equations generally contain an empirical element, but typically have been tested under few actual field situations (Naden 1988, Gomez and Church 1989).

2.3 Measuring Sediment Transport and Channel Changes

2.3.1 Sampling Methods

The coarse sediment transfer can be measured by sampling the streambed as the bed load travels downstream, termed the *direct method*, or by evaluating the stream morphology during or after flood events, termed the *indirect method.*

The direct method involves sampling the sediment as it moves downstream, on or slightly above the streambed. Direct measuring apparatus are typically:

the basket sampler (Ehrenberger 1931, Nesper 1937, Novak 1957),

the pressure-difference sampler (Novak 1957, Hubbel 1964, Helley and Smith 1971, Emmett 1980), slot or pit samplers (Reid et al. 1985, Church et al. 1991, Powell and Ashworth 1995),

in situ magnetic detection devices (Ergenzinger and Conrady 1982, Ergenzinger and Custer 1982, Ergenzinger and Custer 1983, Custer et al. 1986, Bunte 1996, Tunnicliffe 2000).

The total rate of bedload transfer can be computed when the measured streambed transport is combined with the discharge. Sidle (1988), used the direct method approach and sampled Bambi Creek, (Alaska) to determine the rate of bedload transfer using two stream sections approximately 10 meters apart.

The indirect method involves measuring physical characteristics of the stream over a stream-reach. The length of stream reach should be at least one step-length (see section 2.3.2) such that the sampling method does not measure strictly erosion or solely deposition patterns. Note that selecting an appropriate step length distance does not necessarily ensure that the stream section will not be in an erosional/aggradational stage, especially in forced pool-riffle stream morphology (Hogan et al. 1998b.). Measuring bedload transport in a coarse-grained channel can be particularly difficult because flows necessary for transporting larger particles are usually deep, turbid and turbulent, making the direct physical measurement and visual observation of particle motion difficult. Consequently, sediment transfers can be measured indirectly by methods such as scour chains (Colby 1964, Leopold et al. 1964, Carling, 1987, Hassan, 1990, Larrone et al. 1994), tagged sediment tracers (Butler 1977, Chacho et al. 1988, Hassan, 1990, Sobocinsky et al. 1990, Gitnz et al. 1996, Gottesfeld 1998) and morphological methods, which are discussed in the following section.

2.3.2 Morphological Methods for Estimates of Sediment Transport

The coarse sediment budget in gravel bed rivers relates the transport of sediments to the channel morphological features, eg: bars, pools and riffles. Downstream bed material transport is a continuous process where the exchange is manifested in a progression of bed waves (Neill 1987). Neill proposes that in meandering streams, the volumetric transport (Q_s) is related to the bank recession rate (dE/dt), the height of the bank material deposits (h) and the length of travel distance between erosion and deposition (L), or step length.

McLean (1990) attempted to generalize Neill's morphologic method of analysis by using a digital terrain model (DTM) to estimate the volume of bedload transport in the Fraser River. In the absence of regular meanders, the step length was taken as the distance between active deposition zones. Church et al. (1987) demonstrated the potential of the morphologic method on the Mackenzie River, near Norman Wells, using aerial photography and planimetric maps. The average step length was assumed to be the mean distance between successive riffles.

Using the same approach in pool-riffle morphology the step-length would then be the distance comprising one pool-riffle unit. For equilibrium to exist in the step-length reach, the total storage (S) of the reach length should balance between the incoming sediment load (I) and the outgoing sediments (O). Any imbalance between I or O results in an aggrading (positive) or eroding (negative) stream section. These conditions are important considerations when selecting a sampling technique as an aggrading or eroding sampling location could result in over- or underestimating bedload transfer (see also Gomez 1991).

Morphological estimates can also be made by mapping the streambed surface repeatedly, over a period of time. Mapping of the streambed can be done using cross-sections (Griffiths 1979, Martin and Church 1995, Milne and Sear 1997), topographic methods (Lane et al. 1995), sonar (Dinehart 1992), Global Positioning Systems (GPS) (Brasington et al. 2000) and seismic detectors (Govi et al. 1993).

The objective of all of the morphological methods is to create a physical (spatial) model of the streambed over a period of time (temporal). The quality of the spatial model as measured is directly connected to the sampling rate and density. Seismic detectors and sonar mapping techniques provide a continuous recording of the streambed which is valuable, but they tend to have a poor vertical accuracy. A widely used method for evaluating morphometric change is the measurement of stream cross-sections. Stream cross-sections are generally taken perpendicular to the flow and spaced such that the main erosional/depositional changes are addressed. The volume between cross-sections (V_{1-2}) is then calculated by averaging the end areas (A_1 and A_2) and multiplying it by the spacing length (L) (Ashworth and Ferguson 1986, Laronne and Duncan 1992).

$$V_{1-2} = \tfrac{1}{2}(A_1 + A_2)\,L \tag{1}$$

The spacing of the cross-sections is very important. If the spacing is too far apart, the surface morphology between two cross-sections can change (e.g. from pool to riffle), which would not be reflected in the data resulting in a significant error in the calculation of the volume of transport. In Ferguson and Ashworth's paper (1992), they found that, unless the cross-sectional spacing is smaller than two to three meters, significant errors in volume calculations could arise due to undetected erosion and deposition between the sections. Another downfall of the cross-section method is the need to re-measure the same sections in order to account for the dynamic nature of the stream. A more continuous method is required to decrease the stream length and remove the need to have to return to the same cross-section. This would allow the technique to adapt to the changing nature of the stream.

GPS systems have changed tremendously over the last 10 years. The lack of vertical accuracy of GPS made the use of them less appealing in the past. This was especially true in forested areas where the signal was often lost. Brasington et al. (2000), with the aid of a receiver (base station), topographically mapped a 80x200m divided reach section of the gravelly River Feshie, Scotland with a limit of detection of 10cm and daily collection rate of 2000 points with a density of 1.1 points per square meter. Using the approximately 13,000 points, Brasington generated triangulated, irregular network (TIN) surface models that were used to calculate the volumes of change between the 1998 and 1999 surveys. The drawback to this technique was the reported vertical accuracy of 10 cm, or two clast thicknesses. As well Lane et al. (1994) recommended that the survey point density be at least 3.5 points per square meter, in order to detect subtler morphological changes within a stream reach.

2.4 The Sockeye Salmon

Five of the six Pacific salmon species have evolved in the north Pacific coastal area of North America (Pearcy 1992). The five salmon species found in British Columbia include the pink salmon (*Onchorhynchus gorbuscha*), coho salmon (*O. kisutch*), chum salmon (*O. keta*), chinook salmon (*O. tschawytcha*) and sockeye salmon (*O. nerka*). They differ considerably in size, habit and their time of return to fresh waters. Commercially, sockeye salmon is the most valuable (Haig-Brown 1967). In the Fraser River those fish that spawn furthest upstream, and further to the north, enter the estuary earliest. The first commercially important sockeye run each year in the Fraser River is the Early Stuart Stock, which enters the Fraser Estuary in early July (Langer et al. 1992). The sockeye salmon then swim approximately 1500 km upstream to the most northern part of the Fraser drainage system, the Stuart-Takla watershed. Forfar and O'Ne-ell watersheds are sub-drainage systems of the Stuart-Takla watersheds and are important spawning areas for the early Stuart stock.

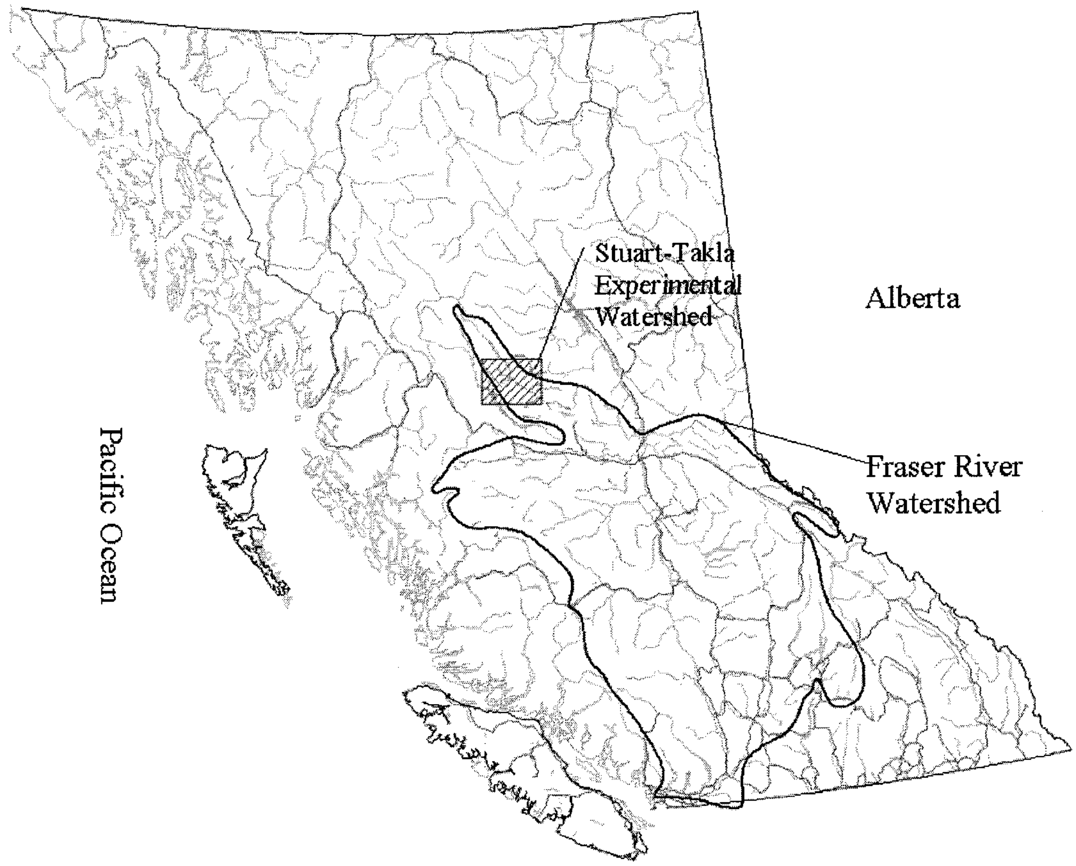

Figure 2: Map of British Columbia with Fraser River Drainage Area

2.4.1 The Sockeye Salmon Cycle

The early Stuart-Takla sockeye salmon has a four-year life cycle. Egg deposition generally occurs in the middle to end of July (Macdonald et al. 1992). The sockeye salmon eggs then incubate for a period of 50 to 70 days (Gottesfeld pers. comm.) depending on stream conditions during incubation. The sockeye salmon emerge as alevins in the stream gravels with the yolk sack still attached for nourishment. In the spring, alevin emerge from the stream gravel as fry to migrate downstream to a receiving lake, where they rear in the lake environment for a one to two year period. The Forfar and O'Ne-ell Creek fry presumably rear for one year in Trembleur Lake. It is thought that some Forfar Creek sockeye salmon fry may rear slightly upstream in Takla Lake.

Following this growing period, the sockeye salmon smolt will begin its downstream migration to the sea, where it will mature in the sea for approximately three years. At age four, the mature sockeye salmon returns to its native stream for reproduction. The female prepares the nest (redd) and lays her eggs, which are fertilized by the male sockeye salmon. The spent salmon die in their native stream, completing their life cycle.

2.4.2 Redd Construction, Spawning and Egg Deposition

During the construction of the redd, the female sockeye salmon typically excavate and fill the entire nest while the male sockeye salmon takes little part in redd building (Foerster 1968). In the early literature, Mathisen (1955) attempted to evaluate this behavior in an experiment in Pick Creek, Alaska, in which two pens were prepared, one with 10 males and 10 females and the other with 10 females. He found that the presence of males served mostly to stimulate females in redd construction activities. McCart (1969), observed that the male salmon will sometimes dig in times of sexual frustration but the digging activities did not appear to make significant contribution to the nest preparation.

Jones and King (1950) investigated the process of redd construction and describe it as follows:

> *"in her cutting [i.e., digging] movements, the female starts from her normal position, i.e., head upstream, body on an even keel and almost parallel to the bed of the river. She then turns over her on side by firstly rotating her caudal fin so that it rests almost flat on or near the gravel, and follows this by a lesser rotation of the rest of her body which in this phase has its dorso-ventral axis at about 45° to the streambed.... A bending of the body follows. In this phase the posterior half of the body is bent sharply downwards and the caudal fin rests fanned out on or near the gravel. The bending of the anterior part of the body is less pronounced, so that the head is often only slightly lower than the middle of the body ...*
>
> *From this position, rapid straightening (the upstroke) and bending (the down stroke) of the body follow so that the posterior region of the body is thrust vigorously upwards and downwards from and to the gravel....*
>
> *It is suggested that the vigorous downstroke of the posterior half of the body thrusts the water against the gravel with sufficient force to loosen it, and that the upward flexion further assists the movement downstream of the displaced gravel by an upward suction... "*

Jones (1959), filmed the redd excavation process and produced a photographic time-series of the digging procedure, shown in Figure 3. Of interest in these photos is the flexing of the female sockeye salmon tail. As stated by Jones and King (1950) by repeating the process shown in Figure 3, the female sockeye salmon excavates the nest for egg deposition.

After the nest is excavated, the female places herself over the center of the "pocket" and the male then joins her. She deposits her eggs and the male releases his sperm. Following the spawning act, the male leaves and the female buries the "pocket" using a technique similar to the digging phase, except that her position is 15 to 30 cm upstream of the nest (Mathisen 1955). The excavated nest tends to have an open gravel face at the upstream end. By using a similar technique to that of nest excavation, she dislodges the substrate from the upstream face of the nest which moves the gravels over the fertilized eggs, filling in the nest. It is suspected that once the substrate has been dislodged from its imbricated position; the downward streamflow assists the female salmon in transporting the gravels over the nest (McCart 1969).

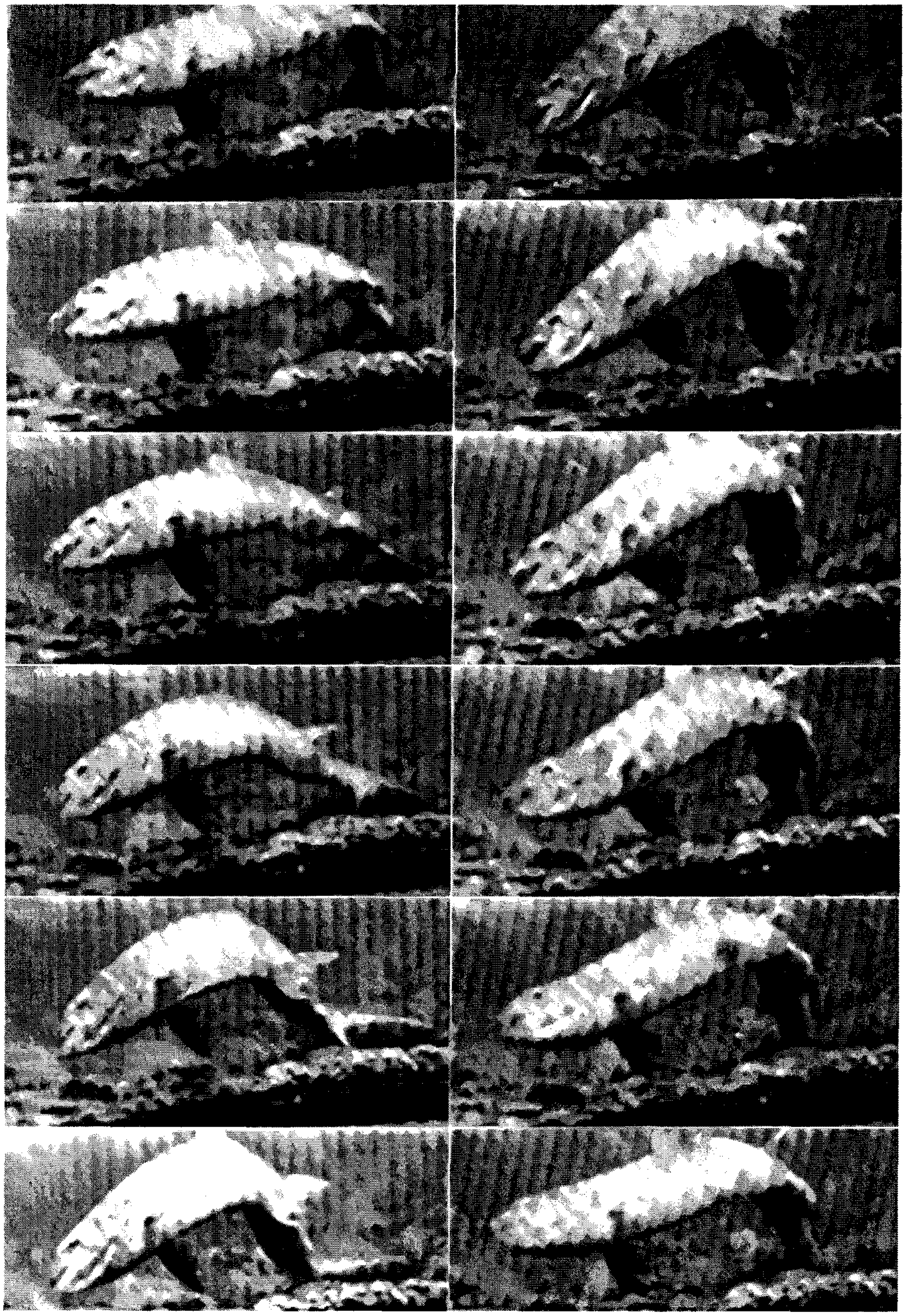

Figure 3: Salmon Digging Sequence (from Jones 1952)

A good diagrammatic representation of a constructed redd (modified from Burner 1951) is shown in Figure 4. The digging process forms a tail spill downstream. A study done by McCart (1969) shows the female sockeye salmon tend to orient with the current, which aids the transport of excavated material. The resulting nest tends to be ovoid, with a long tail spill. Tutty (1986) shows similar patterns of erosion and deposition from a series of redds constructed on the Nechako River. Kondolf and Wolman (1993) conducted a study on the grain size distribution of brown trout redds. They found that there was a slight increase in the content of fines in the tail spill as compared to the upstream section of the redd, with the concentration of coarse gravel in the middle of the ovoid redd. This phenomenon might be purely mechanical and proportional to the stream flows during spawning. Consider also that as the nest deepens the large substrate cannot be easily dislodged downstream while the finer sized bed particles can be mobilized more easily from this lower elevation. It is speculated that, during the burial of the nest, the larger gravel particles will cover the eggs, while the finer particles travel further downstream. Bjornn and Reiser (1991) concluded that nests with larger gravel sizes increase egg survival rates as a result of higher flows associated with the higher streambed porosity of the disturbed gravels. The water flow patterns through the nest, resulting from the redd excavation, were observed to be enhanced in lakeshore and stream environments (Cooper 1965). The benefit of this increased inter-gravel flows is two fold: the removal of waste by-products and an increase in dissolved oxygen within the gravels improving the chance of survival of the deposited eggs.

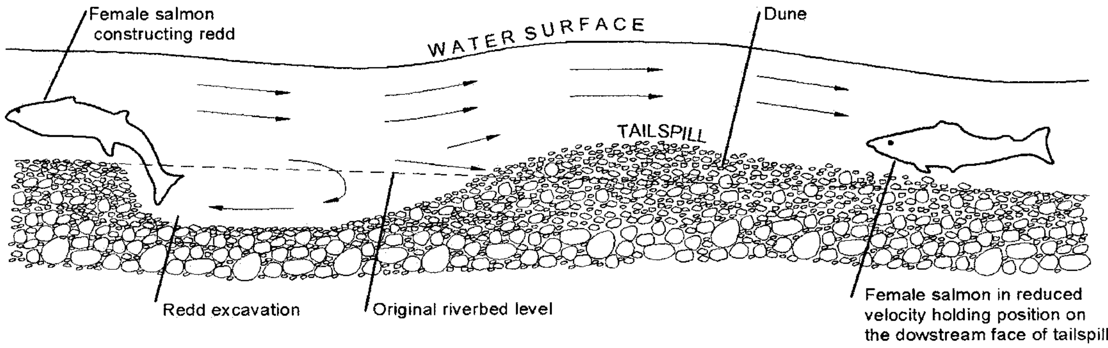

Figure 4: Redd Construction (adapted from Burner 1951)

McCart (1969) measured individual spawning redd dimensions at Four Mile Creek, (Babine Lake, BC), and found that redds averaged 102 x 86 cm with an average depth of 8.9 cm (Table 1). He further noted that redds created in backwaters with no perceptible current tended to be circular in shape, with the excavated gravels distributed as a continuous ridge, 10 to 20 cm wide, around the perimeter.

Measurement	
Number of samples	25
Length of Nest (cm)	
Min	60
Mean	102
Max	170
Width of Nest (cm)	
Min	60
Mean	86
Max	130
Maximum Depth of Nest (cm)	
Min	4
Mean	9
Max	17

Table 1: Measured Redd Dimensions, (from McCart 1969)

Scrivener et al. (1998) used freeze core samples to measure the redd depth in both Forfar and O'Ne-ell Creeks from 1990 to 1998. He found that the average redd depth for Forfar Creek over the 8 years was 20.4 cm and the average redd depth for O'Ne-ell Creek was 20.5 cm.

2.4.3 Sockeye Salmon Enumeration in the Stuart-Takla

Dr. Peter Tschaplinski has enumerated the spatial abundance of the sockeye salmon for both Forfar and O'Ne-ell Creeks for 8 years (pers. comm.). His study consisted of counting the sockeye salmon stock at every 30-metre section from the mouth of the stream to approximately 2.5 km. upstream. Although his work has not yet been published, I have been allowed to include some of his preliminary findings. This provides a more accurate estimate of the number of spawners in the stream section under study. Dr. Tschaplinski's fish counts represent the total number of sockeye contained within a 30 metre section. To assess the female portion of the total count, Tschaplinski's fish count was multiplied by the male/female ratio as measured by the Department of Fisheries and Oceans, Canada for these particular streams and years (1996,1997).

Chapter Three - Methods

3.1 Study Location

The Stuart-Takla/Middle River drainage basin, with approximately 33 tributaries, is at the northern part of the Interior Plateau of the British Columbia physiographic region (Valentine et al. 1978) and consists of the most northern extent of the Fraser River drainage basin (Figure 1). For this investigation, two sub watersheds of the Stuart-Takla drainage basin were selected as study sites (Figure 1). Forfar Creek and O'Ne-ell Creek, approximately 55°00'N latitude, 125°30'E longitude, are important spawning creeks for the early Stuart sockeye run. The Stuart-Takla study site is underlain by the Cache Creek Complex, which consists of metamorphosed fine clastic sedimentary rocks of Pennsylvanian to Triassic age. The Forfar Creek basin and portions of the upper O'Ne-ell Creek basin are situated on a younger (Mid Jurassic to Cretaceous) intrusive body of granodiorite. Most of the Forfar and O'Ne-ell watershed extents are blanketed by tills, with depths usually exceeding 3m in the lower valley reaches (Plouffe 2000). From their headwaters at approximately 1500m, Forfar and O'Ne-ell Creeks descend steeply through outwash fan material that has been incised considerably since the close of the Fraser glaciation (Ryder 1995). The higher elevations consist of Englemann spruce – subalpine fir zone, while the valleys form the northern part of the sub-boreal spruce biogeoclimatic zone (Valentine et al. 1978). Stream lengths are approximately 20 km with the lower 3 to 4 km of the watersheds demonstrating low gradients, ranging from 0.5 to 2 %, and a mean streambed gravel size of 8 cm. Sediment sources in these streams are predominantly from bank collapse, and most of the bedload in transit comes from the streambed itself. The proportion of fine sediment (less than 1 mm) delivered from these systems ranges from 10 to 15 percent and occurs in a period of 3-4 days (Beaudry 1998). Large, woody debris (LWD) is an integral part of these stream sections which exhibit frequent log jams. The introduction of LWD in the stream creates a forced pool-riffle morphology with frequent overhanging trees and shrubs providing excellent habitat for salmon spawning and rearing.

The Stuart-Takla Fisheries/Forestry Interaction Study (STFFS) is a multidisciplinary (fisheries, forestry, hydrology, geomorphology) and multiagency (Department of Fisheries and Oceans, UBC, UNBC, SFU, CANFOR and First Nations) project that has been ongoing in several of the watersheds since 1991. The larger goal of the study is to work towards a better understanding of the relationship between forest harvesting activities and the productive capacities of aquatic environments in the interior of British Columbia (McDonald et al. 1992). The complete list of STFFS projects is too extensive to list here, but includes studies of bed material transport, fine sediment transport, sockeye salmon enumeration and biological condition, precipitation and streamflow measurement and riparian biodiversity. Macdonald et al. (1992) provides a good summary of the individual projects. The study reported here represents one of the individual projects contributing to the larger goal of STFFS.

Air temperatures are warm during June, July and August, which are the only frost-free months, such that the growing season is relatively short compared to more southerly locations. Average annual precipitation in the Stuart-Takla watershed is approximately

50 cm. Summer rainstorms generally occur in the months of June/July and late August/September. Winter precipitation generally occurs as snow during the months of November to March. Thus the two definite flood cycles in the Stuart-Takla watershed are in the nival flood in spring from the snow melt (mid-May to early June) and in the summer or fall during intense precipitation events. Nival discharges are lower in Forfar Creek, averaging 7 m^3/s, and larger at O'Ne-ell Creek, averaging $14m^3/s$ as it incorporates Tsitsutl Creek which enters the O'Ne-ell Creek 1750m upstream of the mouth.

In the Stuart-Takla experimental watersheds, the early timed sockeye salmon stock spawns between July 27 and August 23 (Macdonald et al. 1992). The spawning period most often extends over a period of five to six weeks and can involve 20,000 or sockeye salmon returning to each spawning stream. Over this time period the preparation of redds occurs in the lower stream reaches but during high return years some portion of the streambed are used more than once (Gottesfeld 1998). Due to this reuse of spawning sites it is not possible to use a portion of the spawning period for extrapolation to the entire spawning period to determine the morphometric changes associated with salmon bioturbation.

3.2 The Study Sites

To evaluate the effects of flood events and sockeye salmon spawning on the streambed, two creeks were selected in the Stuart-Takla watershed: Forfar Creek and O'Ne-ell Creek. Forfar Creek and O'Ne-ell Creek are tributaries entering on the west bank of

Middle River. All study sites are between Middle River and the 700-logging road, which provided access to the creeks. The experimental creeks in the Stuart-Takla study had previously been surveyed such that all the stream reaches were categorized by the distance in metres from the mouth.

Two sites were selected on O'Ne-ell Creek (Figure 5), and three sites on Forfar Creek (Figure 6). Localities are named as the approximate channel distance upstream from the mouth. Thus, Forfar 250 is the study site on Forfar Creek, about 250 metres upstream of Middle River. Table 2 is a summary of the stream gradient, study reach width and lengths. The size structure of the gravel bed was characterized by Gottesfeld (1998) who measured the A, B, and C axis of approximately 1610 clasts for all the stream section. This information is included in Table 2.

Stream Section	A-axis* (cm)	B-axis* (cm)	C-axis* (cm)	Sample Size (N)	Stream Gradient	Average Reach Width (W) (m)	Study Reach Length (L) (m)	L/W
Forfar 250	6.99	5.21	3.78	284	0.50%	7.00	23	3
Forfar 1050	8.74	6.30	4.35	304	0.90%	7.12	42	6
Forfar 1545	9.67	7.11	4.64	352	1.70%	6.52	47	7
O'Ne-eel 925	8.40	5.70	3.90	278	0.55%	8.98	37	4
O'Ne-eel 1550	8.49	6.27	4.24	392	0.50%	9.40	68	7

Table 2: Properties of the Study Reaches

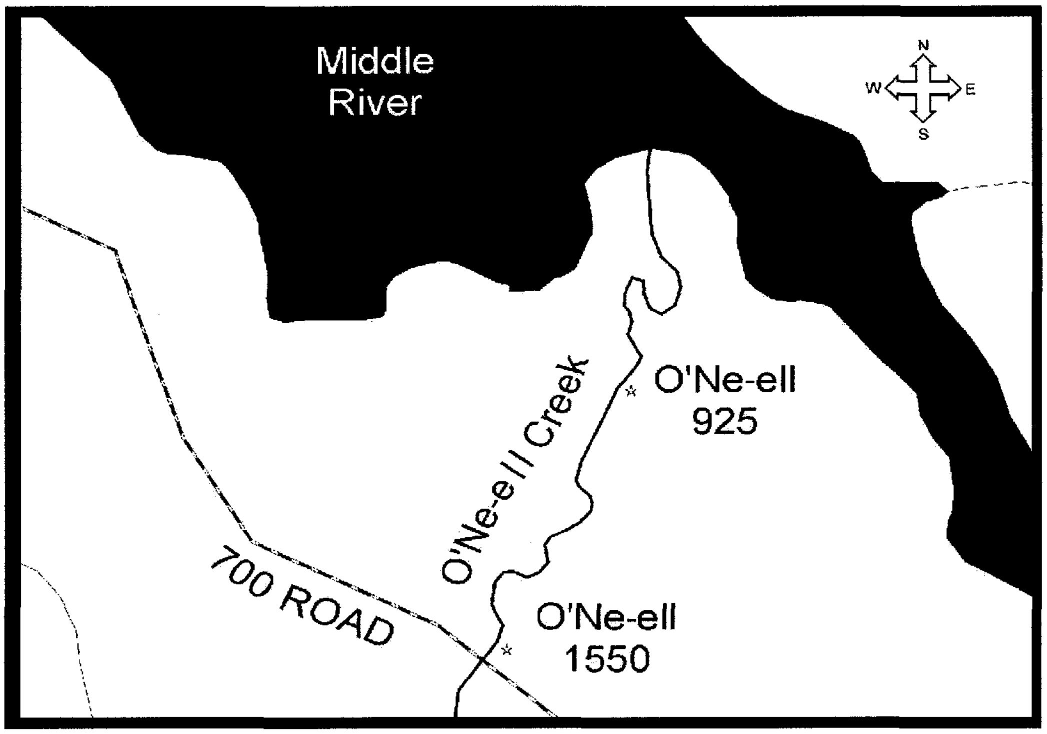

Figure 5: O'Ne-ell Creek Study Sites

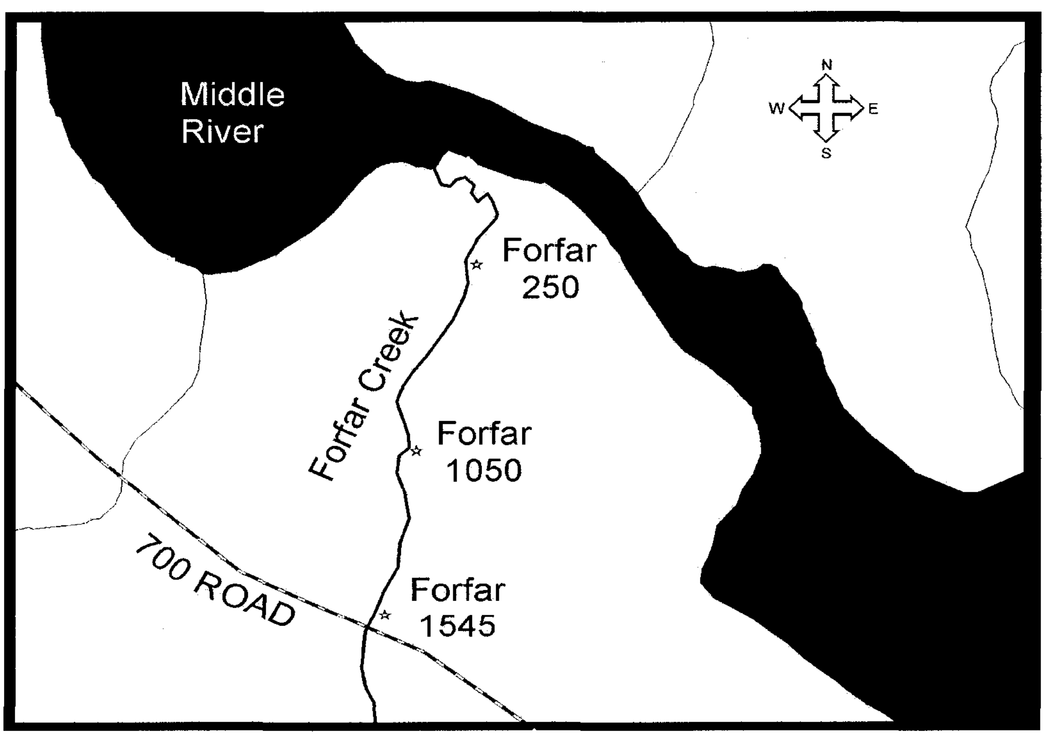

Figure 6: Forfar Creek Study Sites

3.3 Study Timeline

Changes to the streambed were monitored during 1996 and 1997. Three categories of events were measured during the two years of study: nival floods, summer floods, and sockeye salmon spawning. Since bed load movement occurs typically as short discrete events, usually on only a few days of the year, it was possible to characterize the changes by sampling before and after each episode of bed load movement.

3.3.1 Nival floods

In northern latitudes winter precipitation (snow) will accumulate over the surface of a watershed until the spring melt. As the air temperature increases, the melting snow increases the discharge to its adjacent stream. Frontal rainstorms can occur as the snowmelt period is still in progress, further increasing the nival stream discharges. Consequently, these events may be difficult to separate from strictly spring melt nival flows and will be combined and termed nival floods. In the Stuart-Takla watersheds, the nival event generally occurs between the beginning of May and the end of June.

3.3.2 Summer Floods

Summer floods, most often generated by intense convective storms, are most common in July and August around the Stuart-Takla watersheds. As summer convective storms are very difficult to predict, an impromptu streambed survey was required following July 18, 1996 when a summer convective storm occurred. This stream survey was required to separate the effects of the nival flood event from the summer flood event.

3.3.3 Sockeye Salmon Spawning

Sockeye salmon spawning in the Stuart-Takla watershed generally occurs from late July to mid August. The arrival time of the sockeye salmon to spawning streams is partially dependent on the stage and temperature of the Fraser River. High water discharge in the Fraser River or high temperature can delay the spawning time by impeding the progress of the fish progressing to the spawning ground. In 1997 the Fraser River experienced high water discharges resulting in a delay in the arrival time of the salmon. Those that arrived at the spawning ground were extremely stressed. Tsaplanski (pers. comm.) reports that the 1997 spawning success, which is how successful the female sockeye salmon were at depositing their eggs, for Forfar and O'Ne-ell creeks were 74.22% and 76.92% compared to the 1996 spawning success of 96.15% and 95.61% respectively.

3.3.3.1 Sockeye Salmon Enumeration

The Department of Fisheries and Oceans (DFO), Canada has conducted sockeye salmon stock assessments in the Stuart-Takla watershed since 1938. The measurement technique consists of a counting fence installed across the creek at a position near the mouth. A trap system is installed to allow sex determination and counts for female and male sockeye. This assessment provided an estimate of the total number of sockeye salmon entering the stream, and their sex ratio.

The female sockeye counts for Forfar and O'Ne-ell creeks from 1938 to 1998, are shown on Figures 7 and 8. The average female count for Forfar Creek is 5,045 and the average female count for O'Ne-ell Creek is 8,067. Excluding the extreme year, the range of sockeye salmon returning to their native stream is between 1,000 and 10,000 with all years exhibiting similar spawning success. Dr. Peter Tschaplinski (pers. comm.) has been enumerating the spatial abundance of the sockeye salmon for both Forfar and O'Ne-ell Creeks. As mentioned earlier, his study consisted of counting the sockeye salmon stock at every 30 m section from the mouth of the stream to approximately 2.5 km upstream. He has allowed the use of his unpublished data as it provides a better estimate of the numbers of spawners in the stream section under study. To assess the female portion of the total count, Tschaplinski's fish count was multiplied by the individual stream's annual DFO male/female ratio.

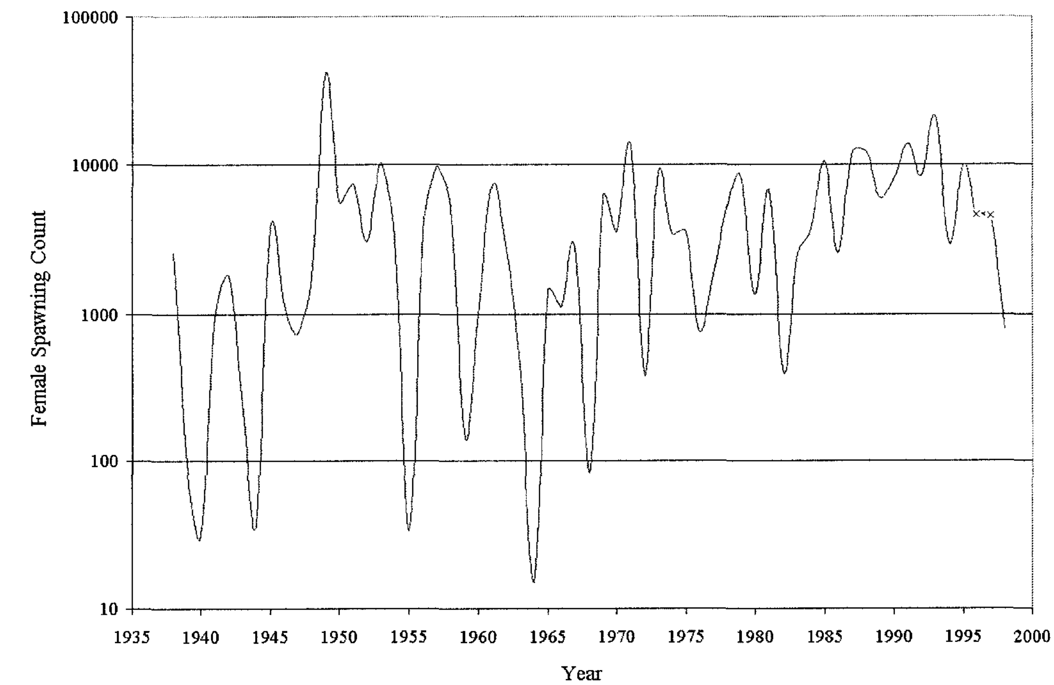

Figure 7: Forfar Creek Female Stock Assessment

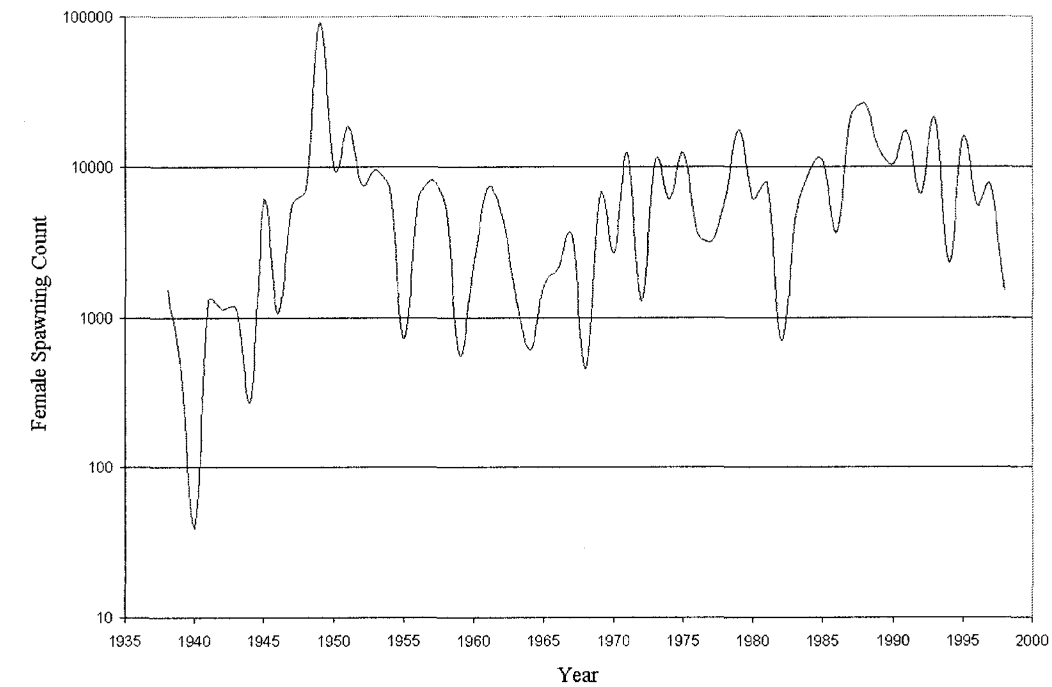

Figure 8: O'Ne-ell Creek Female Stock Assessment

3.3.4 Stream Hydrographs

The 1996 and 1997 Forfar and O'Ne-ell Creeks stream hydrographs are presented in Figures 9 and 10. The Department of Fisheries and Oceans, Canada has been collecting the daily stream flows at the bridge crossing at both Forfar and O'Ne-ell creeks since 1992.

Forfar and O'Ne-ell Creeks, being adjacent watersheds, have similar hydrographs, except for the magnitude of flow which is relative to their basin sizes of 34 km^2 and 68 km^2 respectively. The vertical lines on the hydrographs represent the date at which the streambed was sampled.

In 1996, the stream surveys were conducted early in May, prior to the nival event. The second stream survey was performed in early July following the nival event. On July 18, there was a summer convective storm. Therefore another stream survey was performed on July 27,1996, just prior to the sockeye salmon spawning event. In figure 9 notice how the July summer flood manifests itself in the form of short-duration, high-volume flows, as opposed to an extended period of flow as during the nival flood. Following the spawning event, a final survey was conducted to evaluate the effects of redd construction on the streambed. On both Figure 9 and 10 a line at 3.0 m^3/s illustrates the threshold of bedload motion that was identified by Tunnicliffe (2000) in O'Ne-ell Creek. Note that the stream discharges during the sockeye salmon spawning event are well below his measured flood transport threshold, further establishing the separation of flood transport to that of the redd excavating process.

The 1996 and 1997 peak streamflows for both Forfar and O'Ne-ell Creek were above the 50th percentile of the measured flows. Figure 11 demonstrates that, during the study period (1996 and 1997), the peak flows are higher than average. In a longer flood series, it is likely that the peak stream flows would be average or slightly above average.

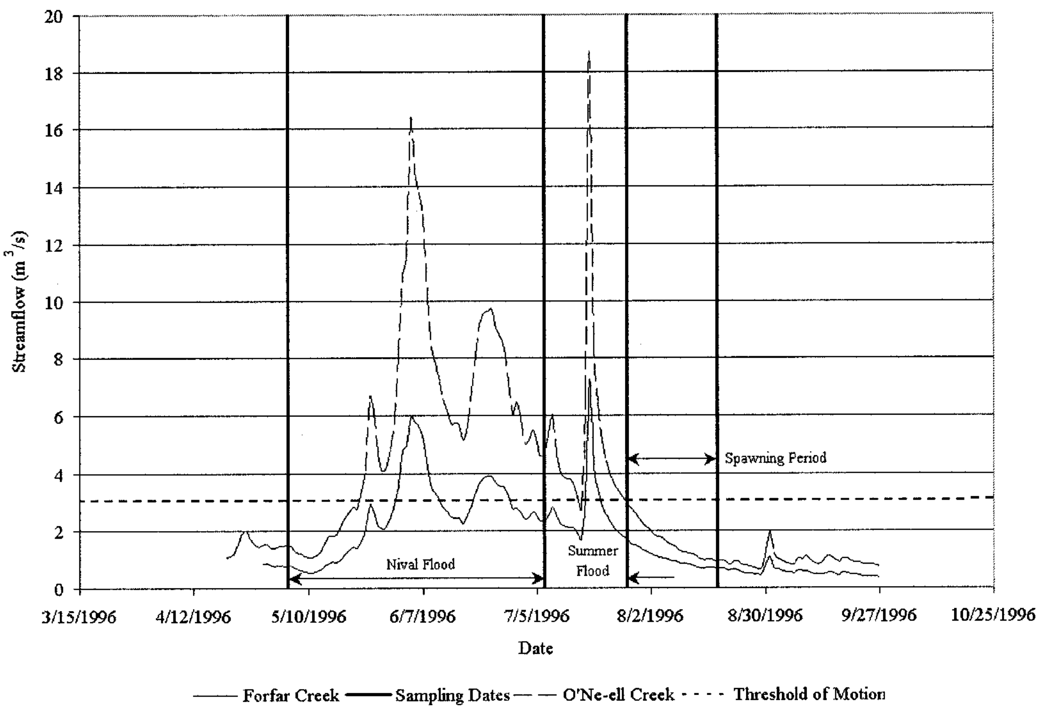

Figure 9: 1996 Stream Hydrographs and Sampling Dates.

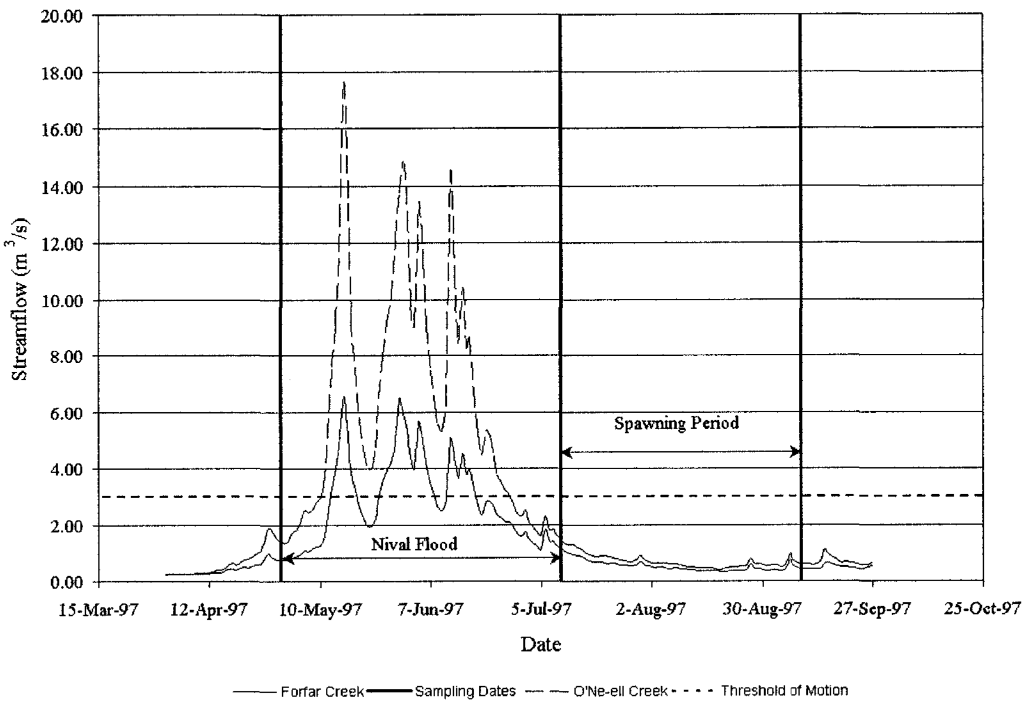

Figure 10: 1997 Stream Hydrographs and Sampling Dates.

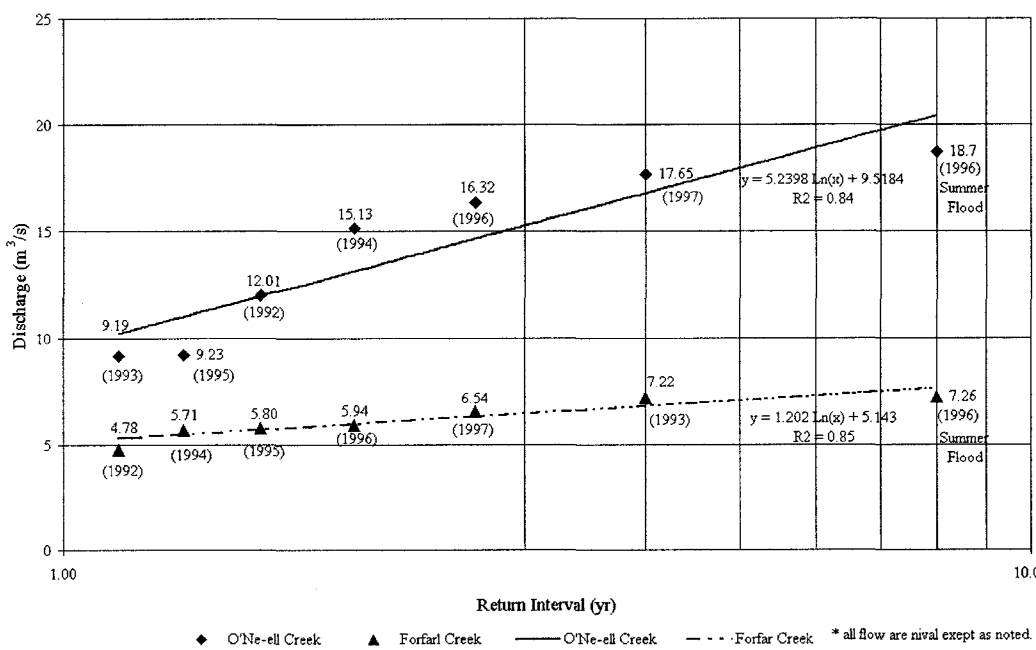

Figure 11: Peak Flow Return Interval

3.4 Survey Method

To create a surface model of the streambed, a sampling method was required. Two approaches were available to map the streambed surface. The first was to measure the streambed surface as a grid, similar to the cross sectional approach. The grid method consists of measuring a surface over a preset grid dimension, using for example a 1-metre by 1-metre grid. This method works well when there is little relief on the surface being surveyed. With the advent of Total Station surveying equipment which allows for fast and accurate collection of many data points, the grid technique offers no significant advantages. The second technique maps the streambed surface by measuring the grade breaks in topography. The surface points collected are the breaks-in-slope and the low/high points over the streambed. The density of the 3-D points collected is then dependent on the frequency of surface changes along the streambed.

The field procedure involved sampling the topography going upstream, moving from the left bank to the right bank (Figure 12). It was found that walking upstream allowed a better view of the mapping surface as the anthropogenic sediment disturbance moved downstream, below the sampler, giving a better view through the water column. Each stream section was surveyed 7 times during the 2 years of research: 4 times in 1996 and 3 times in 1997 (there was no summer flood in 1997) for a total of 35 stream surveys. At each site, a floating elevation was established at the primary survey benchmark and assumed to be 100.000 metre. Over 22,000 individual survey points were collected with an average survey point density greater than 2 points per square metre.

3.4.1 Stream Length Requirements

The stream length required for the study relates to material balance in a stream. The stream section under study must be long enough to ensure equilibrium, as a stream section that is too short might measure only deposition or erosion. Results from Gottesfeld's (1998) magnetic tracer study show that the bulk of the bed load material movement is from one riffle to the following riffle. Therefore, at least one pool-riffle sequence is required. In forced pool-riffle morphology, the pool-riffle distance tends to be smaller due to presence of large woody debris. With his in mind, at least two pool-riffle sequences were measured for Forfar Creek stream sections while three to five pool-riffle sequences were measured in O'Ne-ell Creek stream sections.

3.4.2 The Equipment

Standard engineering survey methods were used to evaluate streambed changes. A series of benchmarks were setup, 10 to 30 metres apart, spanning each of the study stream lengths. A Nikon D50™ Total Station was used as the survey instrument. A range pole with single prism reflector attached to the top was used to reflect the measuring beam back to the survey instrument. The survey rod consists of a straight pole that can be extended up to 4 metres. A prism reflector was attached to the top end of the survey rod.

The Total Station was connected to a Hewlett Packard 48GX™ calculator, set up as a data recorder, to digitally store the survey information on each measured point: the horizontal angle, the vertical angle and the slope distance. This automatic data collection increased the speed and efficiency of the survey method.

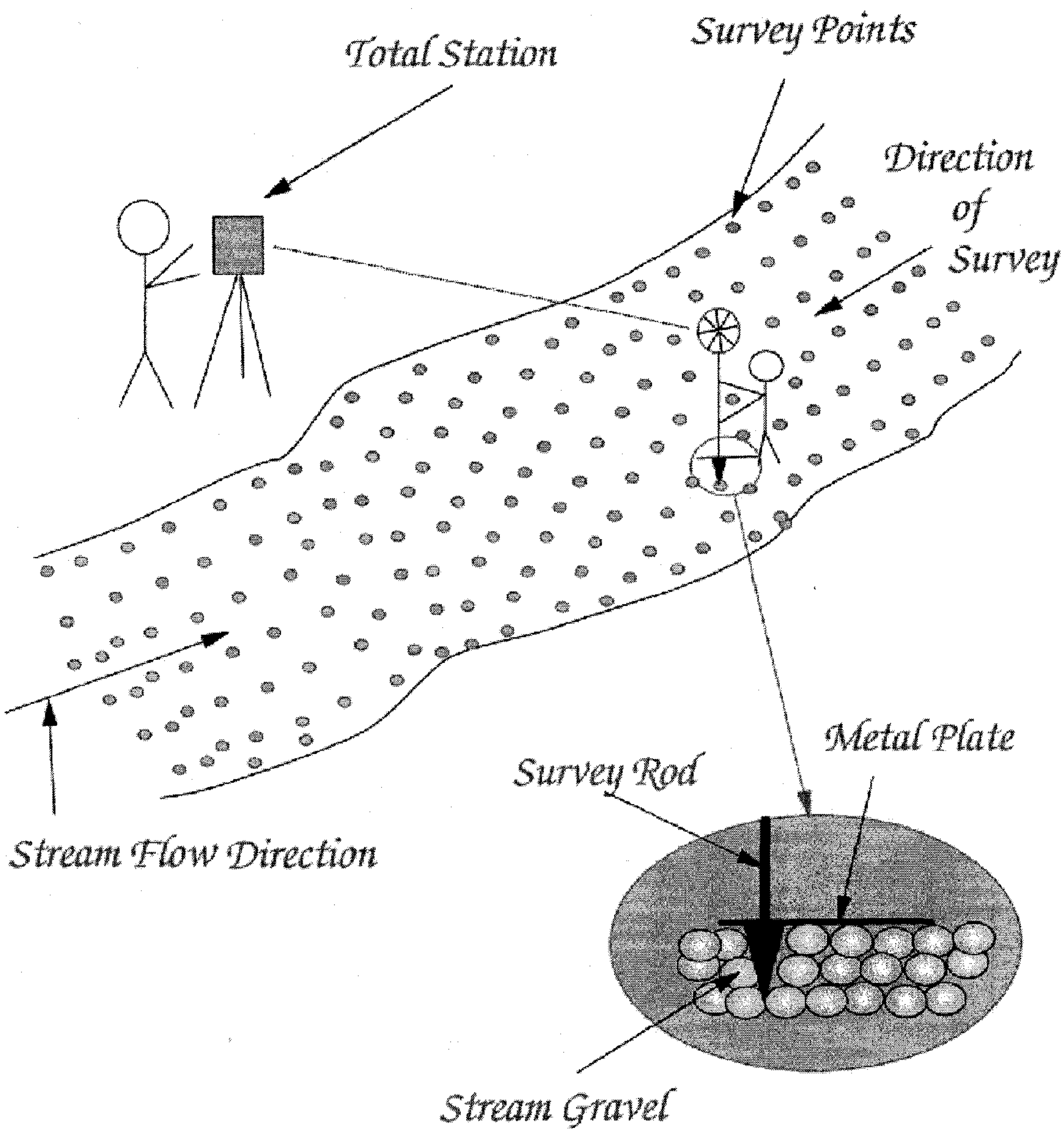

Figure 12: Stream Survey Diagram

3.4.4 Survey Method Accuracy

The accuracy of the topographic survey is dependent on four main factors: human error, vertical and horizontal angular accuracy, laser accuracy, and the nature of the streambed material. Each of these is discussed in more detail below.

3.4.4.1 Human Error

To avoid transcription errors in the field and data entry errors in the office, a Hewlett Packard data acquisition system was used to digitally collect the survey points. This minimized the errors in transcribing the collected topographical points to the field notes and data entry into the computer. The Nikon D-50 Total Station instrument was periodically checked for proper leveling. The reference back sight angle was similarly checked to ensure that the reference angle was always set correctly.

3.4.4.2 Angular and Laser Accuracy

The accuracy in the measurement of reported distance for the total station by Nikon Corporation is reported as $\pm (5 + 10^{-6} * D)$ mm where D is the measured distance in metres. For example, a reported measured distance of 50 m would be accurate to $\pm$ 5.5 mm. To further reduce this error, the total station was generally installed so that the maximum horizontal distance was 25 m, resulting in a total station error of 3 mm. This accuracy was judged to be acceptable for this application given the magnitude of changes in elevation of the streambed reaches studied. There are two angular components measured: horizontal and vertical angles. The Nikon D-50 has an angular accuracy, for both the horizontal and vertical angles of 20 seconds. This angle is the smallest angle that the total station will read. For example, for a 50-metres horizontal distance measurement, the measured vertical position could be in error by 4.8mm. To decrease this error, an attempt was made during the stream surveys to keep the measured distance to a maximum of 25 metres, resulting in a maximum error of 2.4 mm.

3.4.4.3 Compensating for Streambed Penetrability

The total station targets a prism, which is attached to the top of the range pole. The bottom part of the range pole is generally pointed. In the course of my first survey I realized that adequate precision could not be obtained without modifying the survey rod. Using the survey rod with a pointed end bottom to measure the gravel bed elevation of the streambed would be analogous to inserting a straw into a bowl of marbles. The straw would sink in the marbles until the frictional resistance of the marbles counteracted the downward pressure from the straw. The variability of using the survey rod without modification was unacceptably large. To address this problem, a triangular, galvanized steel plate (15x20cm) was constructed and attached to the bottom of the survey rod (Figure 12 and 13).

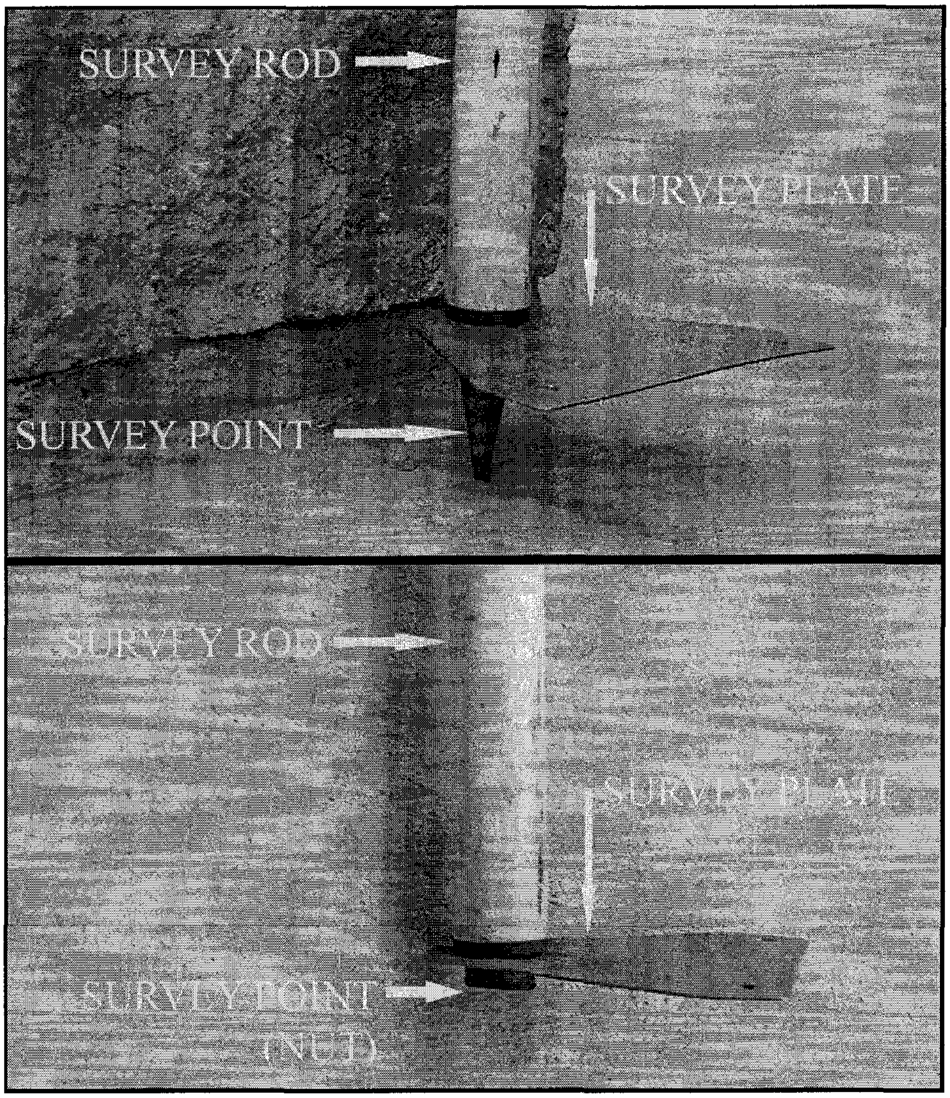

Figure 13: Plate Attached to Bottom of Range Pole

This method enabled repeatability and consistency in measuring the streambed surface. The average streambed elevation was then measured over the plate surface area of 0.0214 m^2 (213.75 cm^2) for each point. The person holding the rod made sure it was firmly on the bottom of the stream and not sitting atop a pebble, by slightly rotating the survey rod from clockwise and counterclockwise. Thereby the average elevation of the tops of the protruding clasts was collected instead of a single point elevation. The point of the survey rod, which extends approximately 66 mm into the gravels, was also replaced by a stainless steel nut. This was done so that the point did not rest on top of a clast thereby inaccurately representing the bedload surface elevation.

To increase productivity, two survey rods were used. Survey rods consist of two cylinders of differing diameters, with a prism at the top and a point at the bottom, that allow the user to slide one against the other to achieve a desired height. It has a brass vertical locking mechanism to ensure that the height of rod stays consistent between collected topographic data points. But under heavy field conditions, the mechanism tends to release causing a possible source of error. To correct for this potential source of error, a hose clamp was attached to the upper section of the survey rod ensuring consistent elevation between collected data points from two sources.

3.5 Sensitivity of the Field Technique

The vertical accuracy of the rod/plate apparatus in combination with the evaluation of stream disturbances other than floods and spawning was required in to determine the operational accuracy of the technique within two stream sections. The first test section was selected to evaluate the effects of investigators walking on the streambed while the second test section was to measure the effects of over-wintering on emergent gravel.

3.5.1 Riffle Test Section

A riffle test section, approximately 2.5m wide by 2.5m long, located just above the O'Neell 1550 study site, was surveyed initially. After the survey, the crew walked repeatedly and vigorously over the test section. A second survey on the same section was then obtained. The volume of bed load change is calculated by creating Triangular Irregular Networks (TIN) for each of the surveys and then determining the volumes of change by calculating the difference between the two TIN's. The volumes were then converted to an average vertical elevation by dividing the volume of change by the plan area (m^3/m^2). The volumes are reported as 'fill' for positive values and 'cut' for negative values from a plane elevation of zero. Zero implies no change.

It was found that the average depth of cut was –0.008 metres while the average depth of fill was +0.001 metres. This indicates that the effect of walking on the streambed was to compress the bed load material more than to create higher ridge areas. By taking the absolute difference between the two, the accuracy of the method combined with anthropogenic disturbance was evaluated. The resulting changes are estimated at 0.007 m indicating that the compaction effects of walking over the streambed combined with the vertical accuracy are less than 1 cm. From this experiment we can estimate an operational accuracy of the survey at 0.008 m, accounting for the effects of the survey crew walking over the streambed surface. This result implies that any reported stream changes that are greater than 1.0 cm are real changes on the streambed.

3.5.2 Emergent Gravel Bar

To test the validity of the survey method under field conditions, an emergent gravel bar on Forfar stream section 250 was surveyed first, following the sockeye salmon spawning event and secondly, following the following year in the pre nival event. As there is no significant disturbance to the emergent gravels during spawning no changes were expected during this period and thus offered a means of testing the accuracy of the method over a period of time. This test section reports that the average depth of cut was 0.012 m while the average depth of fill was 0.004, which agrees well with the previously measured test section.

The gravel bar was used as a staging area for this survey and a marked gravel recovery operation and therefore had been disturbed by foot travel. We may assume that the level of disturbance was much less than that of the intentionally disturbed plot discussed above. Some consolidation of the gravel on the gravel bar could have occurred, but this cannot be confirmed. These results demonstrate an achieved survey accuracy of 8 mm. This concurs with the previous estimate that changes in elevation of greater than 1 cm are real and significant.

3.6 Data Analysis

3.6.1 Surface Modeling

The original data from the 35 surveys was converted to X, Y, Z coordinates and saved as ASCII files. A LISP™ program was written to upload the coordinate file into Autocad™ for conversion to surface models. Eagle Point™, an engineering/earthworks software package, was then used to (i) create the surface Triangular Irregular Network (TIN) model, (ii) calculate the volumes of change for each event, (iii) create the grid surface models used for rendering, and (iv) create the isopach maps to delineate the areas of change within the stream section.

3.6.2 Stream Power

The concept of stream power was first introduced by Bagnold (1966) and is analogous to that of an engine able to exert power to perform sediment-transporting work. Bagnold introduced the following relationship to quantify the stream power of a given flow.

$$\Omega = \rho g S(d\mu) \qquad (2)$$

where:

Ω is the stream power (kg·m/ s^2),
ρ is the fluid density (kg/m^3),
g is the acceleration due to gravity (m^2/s),
S is the energy gradient of the flow (m/m),
d is the depth of flow (m), and
μ is the mean velocity of the flow (m/s).

Generally, bedload transport is related to periods of high flow or peak flows. As a means of comparing flood events to that of biturbation events, the concept of stream power was modified in this thesis so that the average stream power was calculated for the entire event duration. This was done by calculating the daily stream power, summing it up, and dividing it by the total numbers of event days. The resulting stream power provided a means of comparing the energy associated with the nival floods, summer floods and redd excavation events.

For example, in 1996, the pre-nival flood stream survey occurred on May 6, 1996. The post-nival streambed survey was conducted on July 8, 1996. A period of 63 days passed between the surveys. Using the daily discharge measurements, the stream power was calculated over the 63-day period. For Forfar 250 1996 nival flood, the total stream power was calculated as 78,002 kg m/s^2. Dividing the total stream power by the difference of day counts between surveys then normalized the stream power. Using the previous example, the average stream power was calculated to be 1261 kg m/s^2/day.

	Forfar			O'Ne-ell	
	250	1050	1545	925	1550
Stream Gradient (%)	0.5	0.7	1.7	0.55	0.5
Event	Stream Power (kg m/s^2)				
1996 Nival Flood	1261	2272	4291	3177	4736
1996 Summer Flood	1311	2360	4458	2815	4197
1997 - Nival flood	1268	2466	4658	3265	4867
1996 - Spawning Period	481	865	1634	845	1259
1997 - Spawning Period	275	464	876	369	550

Table 3: Normalized Daily Stream Power

Chapter Four

Results

4.1 Introduction

To demonstrate the effects of flood related bed load transport and the redd excavation (bioturbation) over the streambed surface, the stream survey results are presented first followed by the qualitative results (shaded relief diagrams) and finally the quantitative approach (calculated volumes and isopach maps).

The stream survey results are presented first to demonstrate how the surface elevation changes from one event to another. The shaded relief diagrams are then presented to visually delineate how the streambed is modified due to the flood related processes and bioturbation activity. The resulting surface topography is presented graphically and described so that an assessment of the similarities and differences between the two separate processes can be made. The calculated changes in bed load volume are then presented and compared for each of the processes.

The total bed load volume is used as a mean of demonstrating the magnitude of change resulting from each process. This quantitative comparison is important in demonstrating the relative magnitude of each process, allowing an evaluation of the questions: are the flood related processes and bioturbation activities the affecting the volume of material equally, or does one process dominate streambed disturbance? The elevation depth of change, as determined from volumetric calculations directly examines the question of aggregate economy (gains or losses) within the reach thereby indicating if the section is aggrading or being eroded.

Finally, a series of isopach maps are presented. Isopach maps show the aerial distribution of some variable quantity in terms of lines of equal or constant value. Isopach maps offer a means of visually describing the patterns of erosion and deposition over the streambed by grouping the surface changes. This is particularly useful in comparing and contrasting the bioturbation and flood related processes.

4.2 Stream Survey Comparisons

To demonstrate how the stream surface elevation changes between surveys the average elevation was used as a mean of comparison. The average elevation is obtained by taking the average elevation of all the survey points. While average elevations may vary from survey to survey, as the streambed elevation varies from season to season, it is expected that unless the whole stream section under study is aggrading or eroding, the average streambed elevation should remain relatively stable over time provided that an appropriately long stream section is surveyed. Although this technique provides a mean of relating one survey to another, it is important to understand that the calculated average elevation also incorporates the stream gradient. It is only used here to compare the overall state of the stream sections between events, as reductions in average values reflect gross erosion while increases indicate general aggradation.

Extremes in average elevation between surveys might call into question the reliability of the survey elevation information. It is important to note that the calculated average elevations for each creek reach are similar over the 16-month period (Table 4). A local elevation of 100m was used, as a benchmark, for all the stream sections. The standard deviation of the mean for the elevation is also calculated to describe the variability within the stream section for a given event. It can be used to indicate the relative depth of impact on the stream for each event. A summary of these calculations is presented in Table 4.

	FORFAR						O'NE-ELL			
	250		1050		1545		925		1550	
Timing and Event	AVG (m)	STD (m)	AVG (m)	STD (m)	AVG (m)	STD (m)	AVG (m)	STD (m)	AVG (m)	STD (m)
May-96 Pre Nival Flood	99.38	0.12	98.47	0.14	99.35	0.30	98.87	0.17	98.24	0.25
Jul-96 Post Nival Flood	99.45	0.20	98.56	0.23	99.20	0.33	98.85	0.22	98.37	0.36
Jul-96 Post Summer Storm	99.46	0.20	98.54	0.23	99.14	0.35	98.80	0.22	98.33	0.38
Sep-96 Post Spawning	99.35	0.17	98.57	0.23	99.26	0.29	98.79	0.17	98.31	0.32
May-97 Pre Nival Flood	99.27	0.10	98.55	0.20	99.28	0.33	98.84	0.17	98.25	0.25
Jul-97 Post Nival Flood	99.34	0.15	98.51	0.22	99.25	0.30	98.75	0.23	98.29	0.34
Sep-97 Post Spawning	99.30	0.11	98.56	0.20	99.10	0.20	98.60	0.19	98.18	0.31

Table 4: Summary of Average Elevation (m) and the Standard Deviation for all Stream Reaches Studied.

For example, at Forfar 250 the 1996 nival event resulted in a change in average elevation from 99.38m to 99.45m indicating a 0.07 m aggradation over the stream section. The summer flood event resulted in an average aggradation of 0.01m (from 99.45 m to 99.46m), indicating very little change. The average streambed elevation following a redd excavation event was 99.35m, representing an average erosion of 0.11m. For the same stream section, the standard deviation of the pre nival flood surface has a value of 0.12. The standard deviation then increases to 0.20 for the nival and summer flood. This demonstrates an increase in variability of the surface elevations. Following the redd excavation event, the standard deviation decreases to 0.17. This trend of the standard deviation in which the post-flood surface shows higher standard deviations than the redd excavation surface is consistent over all the stream sections for both years.

4.3 Shaded Relief Diagrams

4.3.1 Introduction

Contour maps are traditionally used to visualize surface features. By drawing lines of equal elevation, the surface changes can be interpreted, as the contours are a discrete representation of surface topography. Contour maps are usually presented in plan view and are a two-dimensional representations of a three dimensional model. This approach was evaluated for this project and was rejected because the high density of contours, required to reflect the detail of the survey, generated maps that were too cluttered and difficult to interpret.

To address this problem, shaded relief diagrams were selected as a means of providing a continuous surface representation of the streambed. Shaded relief diagrams provide an oblique perspective, which permits a more natural/conceptual view of the changes that occur.

Shaded relief diagrams are obtained by rendering a grid surface produced from the triangular irregular networks (TIN) surface models. The rendering process applies a texture to the surface model providing a continuous topography. This procedure has the advantage of permitting a visual examination of the surface morphology over the streambed.

The shaded relief diagrams are all positioned such that the streamflow direction is from the left to right of the diagram. Also, since the diagrams are organized in three dimensions, the diagrams must be visualized as if you are looking upstream from a bird's eye view. Dark contrast represents sharp changes in elevation such as at the peaks and depressions points (Figure 14). Shaded relief diagrams allow the visualization of surface features, such as the pools and riffles existing on the streambed. Another advantage of using shaded relief diagrams is the ease of comparing and contrasting the streambed surface changes from one time period to another.

The five stream sections were surveyed seven times in total, four surveys in 1996 and three surveys in 1997. Thus, thirty-five shaded relief diagrams were produced in total (Figures 14 – 48). To accentuate the vertical surface relief of the streambed, the vertical scale is exaggerated four times. For each stream reach, the horizontal and vertical scale has been kept the same to allow a temporal comparison. The diagrams vary in length depending on the distance of stream surveyed. The length of survey varied due to factors such as winter conditions, a decision to increase the size of test sections and/or the addition of extra readings. While the visual comparisons of the reaches may vary slightly in size, note that all numerical comparisons are done on only that region of the reach that is common to all seven surveys. By using a time series of shaded relief diagrams, the relative magnitude and pattern of change occurring from flood related events and redd excavation can be observed.

The objective of presenting this series of shaded relief diagrams is to demonstrate the streambed changes resulting from two separate agents and to determine their effects on the patterns of erosion and deposition on the streambed. The streambed changes for Forfar and O'Ne-ell Creeks are presented in the next four sections with the 1996 pre nival flood shown first, followed by the post nival flood, the post summer flood and finally the post spawning (redd excavation) event. The 1997 data follow in the same order but do not include a summer flood.

4.3.2 Pre Nival Flood

The pre nival flood surface demonstrates the surface morphology prior to the spring snowmelt. This survey acted as a baseline for the year's set of surveys. If no fall or winter flood occurred during the previous eight months, the surface morphology created by the action of the sockeye salmon spawning, the previous August and September, is expected to remain. If streambed modification occurred during the winter months, it will be apparent on the streambed. Observations of the streambed between post spawn 1996 and pre nival 1997 indicate minor changes that can be attributed to intrinsic factors such as compacting of the gravels, anchor ice on the gravel bars or extrinsic effects such as digging on the streambed by large wildlife. Unfortunately, no adequate flow measurements or precipitation measurements were obtained over the winter of 1997. The pressure transducer measuring stream flow froze resulting in a series of erroneous flow measurements. No volumetric calculations were performed for the winter of 1997, as these problems restricted adequate analysis.

At Forfar 1050 the pre nival flood survey in 1997 (Figure 25) demonstrates a surface little changed from that of the previous August 1996 (Figure 24). The pre nival flood surface retains the hummocky surface morphology established from the bioturbation event. Comparing the Forfar 250 1997 pre nival flood surface (Figure 18) to the previous year's post sockeye salmon spawning surface (Figure 17), the pre winter surface morphology appears hummockier that that of the post winter streambed surface especially in the upstream surface.

At O'Ne-ell 925 substantial change is evident between the 1997 pre nival flood surface (Figure 39) and the 1996 post spawning shaded relief diagram (Figure 38). The hummocky features that are observed in the post spawning event surface have been smoothed tremendously after the 1997 winter. This is also evident in the O'Ne-ell 1550 stream section (Figure 45 and Figure 46) and suggests that a 1996 fall flood or a 1997 winter event occurred.

In summary, the pre nival shade relief diagrams show the retention of morphological pattern derived from the previous year's sockeye salmon bioturbation. The changes that occurred within the stream section over the winter season indicate the possibility of a minor fall or early spring thaw flood event. The changes are more pronounced in O'Ne-ell Creek than they are in Forfar Creek.

4.3.3 Post Nival Flood

Following the spring snowmelt, the streambed surface morphology changes from hummocky to planar. The topography is more streamlined, exhibiting a smoother streambed surface. In most cases, a more definite stream thalweg is reestablished. A good example of this process is at O'Ne-ell 1550 in 1996. The surface morphology is altered from hummocky (Figure 42) to linear (Figure 43). Following the spring flood marked changes are especially obvious in deeper pools, which are scoured and as well the riffle stream section appears to be more uniform.

Another good example of nival flood changes is found at Forfar 1050 in 1997 (Figure 25 and Figure 26). Comparison of the post nival flood shaded relief with the pre nival flood surface shows a marked change from hummocky to planar. Again a deepening of the pools can be observed. The gravel bar surfaces show a reduction in the number of hummocks and a decrease in their number. The post nival Forfar 250, 1997 stream section (Figure 19) is interesting in that the stream flow diverges at the upstream end and converges at the downstream section. The resulting streambed morphology indicates a more definite pool-riffle pattern on the streambed.

The higher stream power sections, such as O'Ne-ell 1550 (Figures 43 and 47) and Forfar 1545 (Figures 29 and 33), appear to have a more marked change in their pools than the lower stream sections, O'Ne-ell 925 (Figures 36 and 40) and Forfar 250 (Figure 15 and 19). The nival flood surface changes on Forfar 250 are of smaller magnitude that those at Forfar 1050 (Figures 22 and 26). Notice the point-bar aggradations at the upstream end of Forfar 1050 (Figure 26). The linear or planar aspect of these post nival flow surfaces reflects the erosion patterns of fluid flow over the streambed and the development of a more definite pool-riffle morphology.

4.3.4 Summer Flood

In 1996, a summer rainstorm occurred on July 17,1996 near the end of the nival flood season. At the climate station 1 km north of Forfar Creek 44.3 mm of rain was recorded between July 17 (5:15am) and July 19 (6:00pm). This storm resulted in peak discharges of 7.26 m^3/s in Forfar Creek and 18.7 m^3/s in O'Ne-ell Creek. These high flows were short lived with a total duration of approximately 48 hours. This summer flood resulted in significant bed load movement for both Forfar Creek and O'Ne-ell Creek stream sections. The surface morphology of the streams demonstrates an increase in planar features in which pools are further deepened resulting in downstream movement of the riffles.

At Forfar 1050, with a stream gradient of 0.7% (Figure 23), a small increase in linearity and gravel bar growth is observed on the downstream end of the diagram. Notice the deepening of the pool at the mid section of the stream. There is also a marked growth and advance of the downstream gravel bar, compared to Figure 22. The mid-section bar also shows this feature. The upstream pool is deepened and extends further upstream. Forfar 1545, 1996 (Figures 29 and 30), with a stream gradient of 1.7% demonstrates the greatest magnitude of change over the streambed while O'Ne-ell 925 (Figure 37) and

O'Ne-ell 1550 (Figure 44) demonstrate similar patterns of erosion and deposition, but with less extreme vertical change.

In summary, the summer flood activity tends to accentuate the linear/planar features previously established by the nival flood. The pools are deepened and the gravel bars and riffles expand. It also appears that the impact of floods on the stream increases with increasing stream gradient as stream sections with higher gradients have more stream power resulting in larger morphological changes on the streambed. This correlates well with the observed relationships of stream power and bed load movement (Martin and Church 2000). The topography resulting from these floods demonstrates the morphology the stream section would assume if there were no salmon redd excavation effects on the stream.

4.3.5 Post Redd Construction

Changes in streambed morphology resulting from the bioturbation process are localized, forming hummocky surface features. The stream reaches with lower gradient and finer grained substrate tend to have better-developed hummocky features than higher gradient and coarser grained stream sections. The dislodged substrate from the redd construction moves downstream so that the pools, being the deepest part of the stream, tend to fill with these displaced gravels. At these discharges the stream power of the stream is inadequate to transport the gravels so the bed load material rests at the bottom of the pool until such time as it can be remobilized, usually during the nival flood of the following year.

Following redd excavation by the sockeye salmon in July and early August; the appearance of the streambed is dramatically changed. The linear/planar-streamlined features formed by the floods earlier in the year are replaced by hummocky morphology. This is conspicuous at Forfar 250, 1996 (Figure 17). The lower gradient stream section is the preferred spawning grounds and tends to be heavily used during spawning time.

Further upstream, at Forfar 1050 (Figure 24), the spawning density was slightly decreased. Although the deep pool in the mid upstream section shows some changes due to bioturbation effects, it is clearly not the preferred area of spawning. This pool tends to receive substrate input from the upstream section riffle. The lower downstream riffle reflects the markedly higher spawning density. At the higher stream gradient section at Forfar 1545, 1996 (Figure 31), stream changes are subtler but can still be recognized. The upper riffle shows evidence that the streambed has been changed slightly with some infilling on the downstream pool.

In summary, the effects of sockeye salmon spawning on the streambed tend to create hummocky features over the streambed. The riffles tend to be preferred spawning areas and are therefore highly bioturbated. The pools are relatively little changed by bioturbation. They act, as temporary storage sites until the stream flows are high enough to transport the accumulated sediment to the next gravel bar. The following spring nival event generally re-excavates this bed load prior to deepening the pools. The lower stream reaches tend to show the effects of increased spawning density compared to higher gradient stream sections.

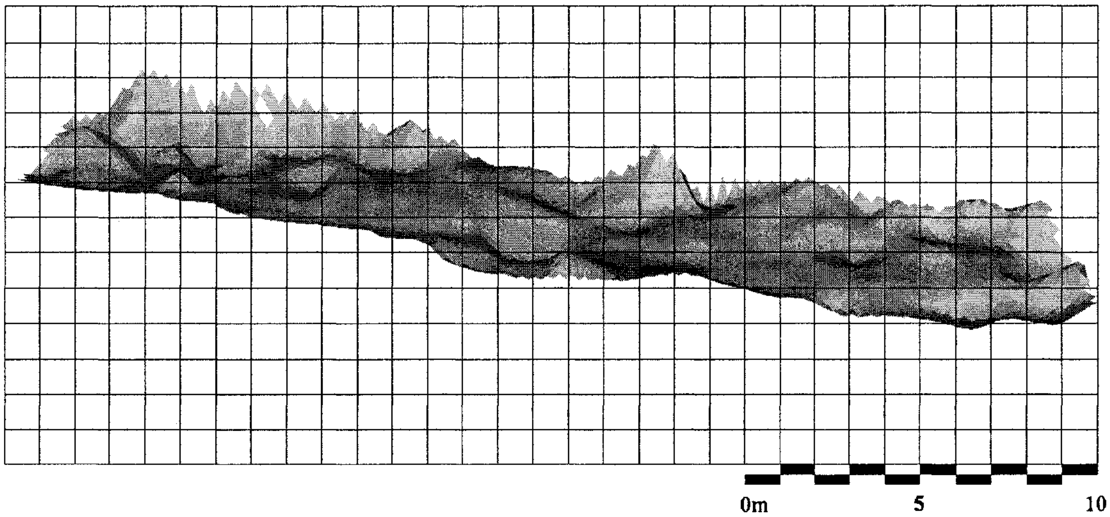

Figure 14: Forfar 250 1996 Pre Nival Flood Shaded Relief Diagram

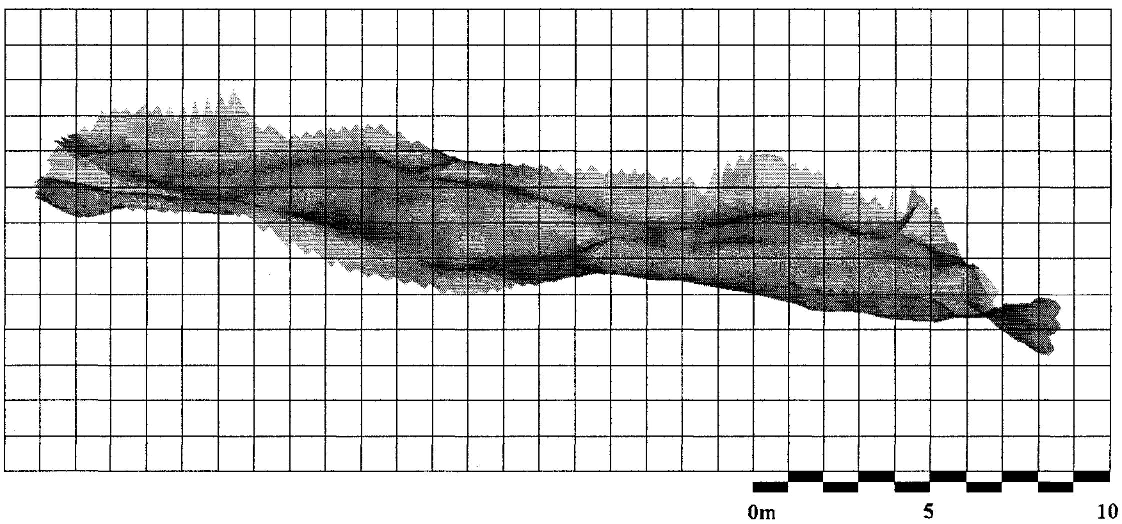

Figure 15: Forfar 250 1996 Post Nival Flood Shaded Relief Diagram

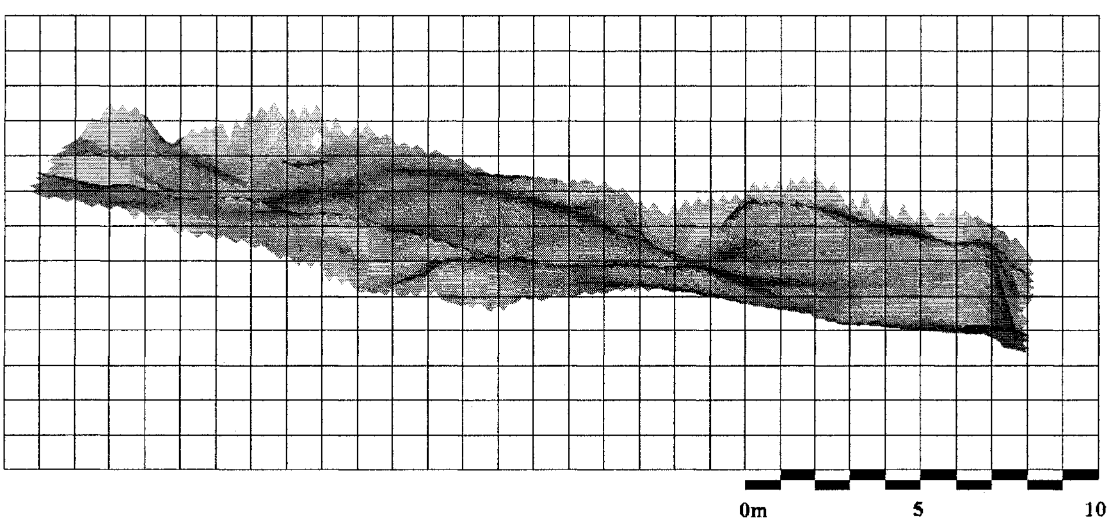

Figure 16: Forfar 250 1996 Post Summer Flood Shaded Relief Diagram

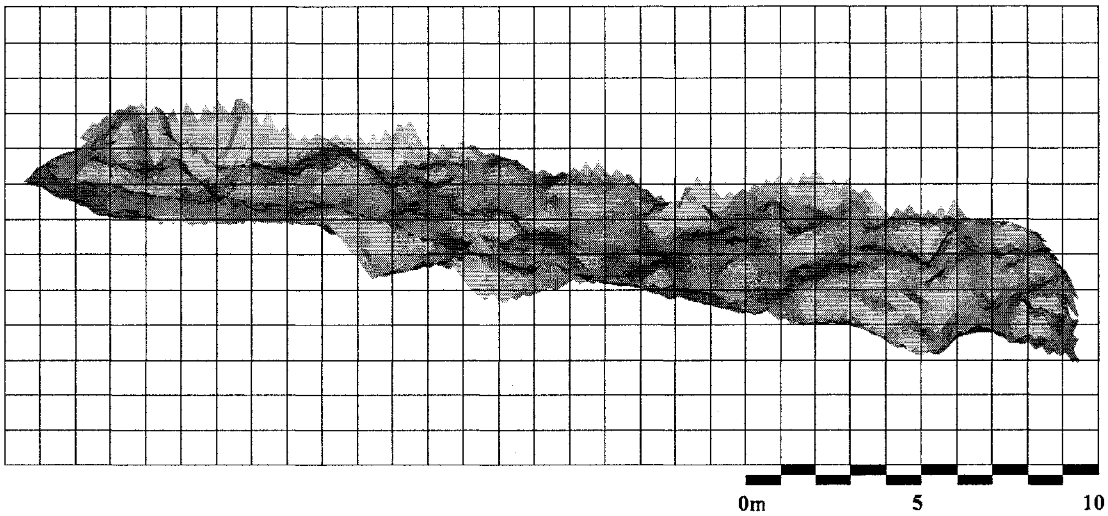

Figure 17: Forfar 250 1996 Post Spawning Event Shaded Relief Diagram

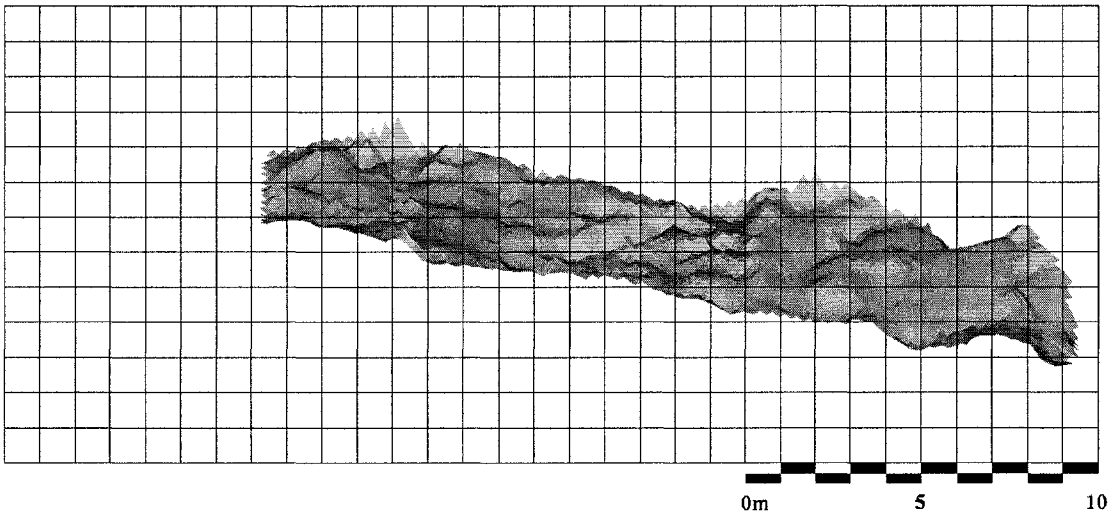

Figure 18: Forfar 250 1997 Pre Nival Flood Shaded Relief Diagram

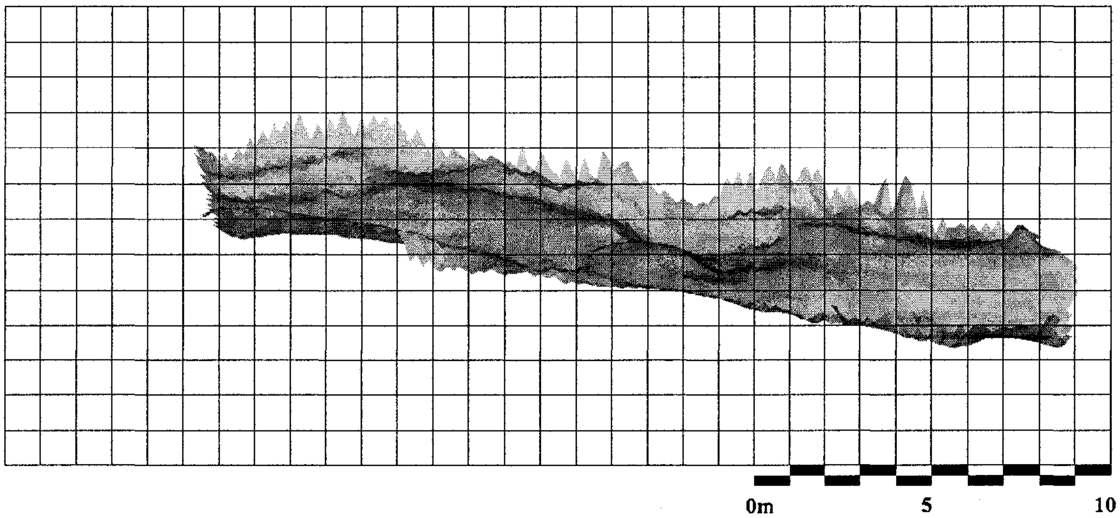

Figure 19: Forfar 250 1997 Post Nival Flood Shaded Relief Diagram

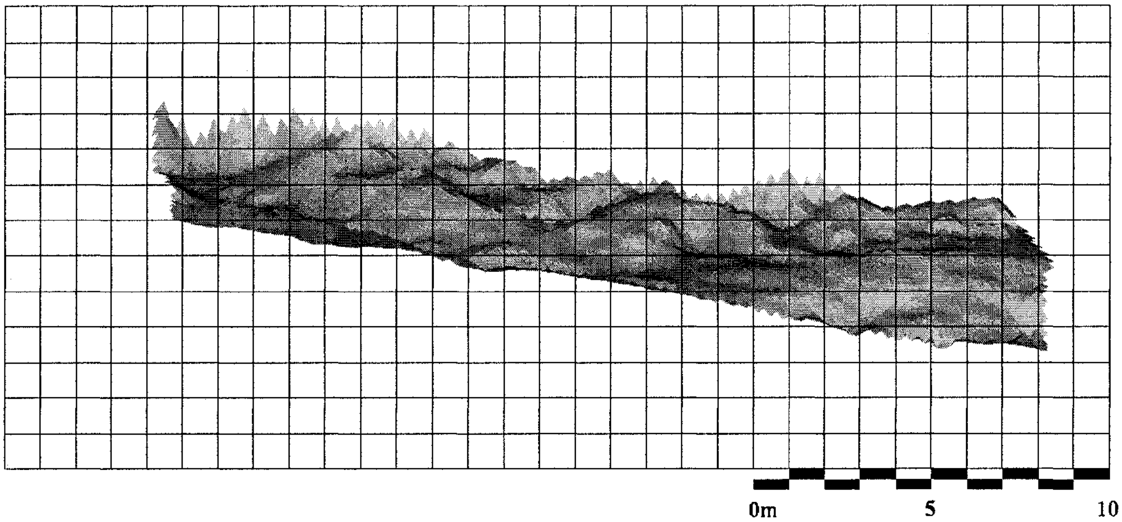

Figure 20: Forfar 250 1997 Post Spawning Event Shaded Relief Diagram

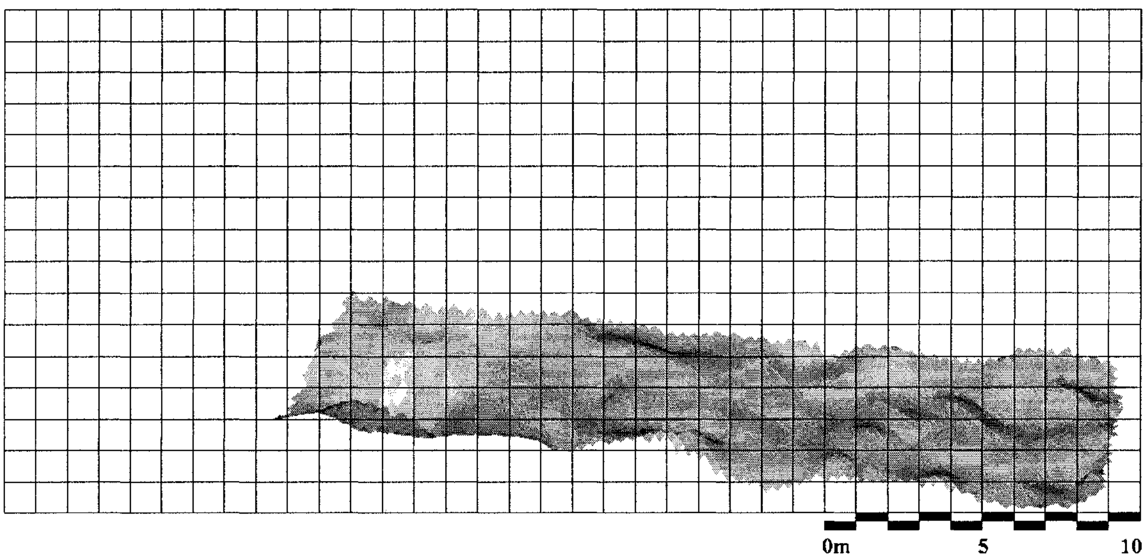

Figure 21: Forfar 1050 1996 Pre Nival Flood Shaded Relief Diagram

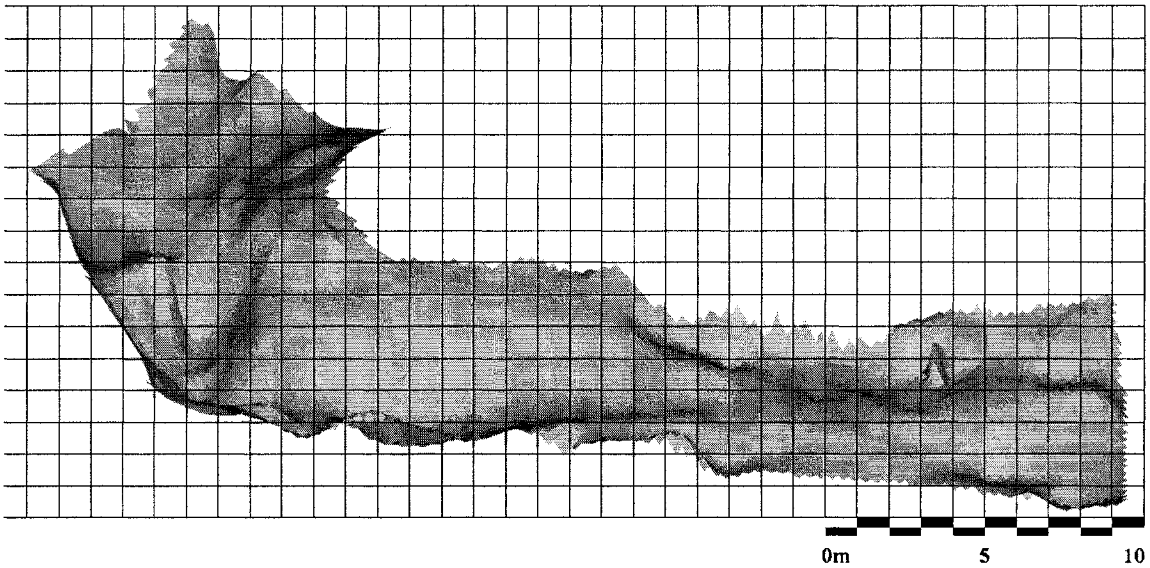

Figure 22: Forfar 1050 1996 Post Nival Flood Shaded Relief Diagram

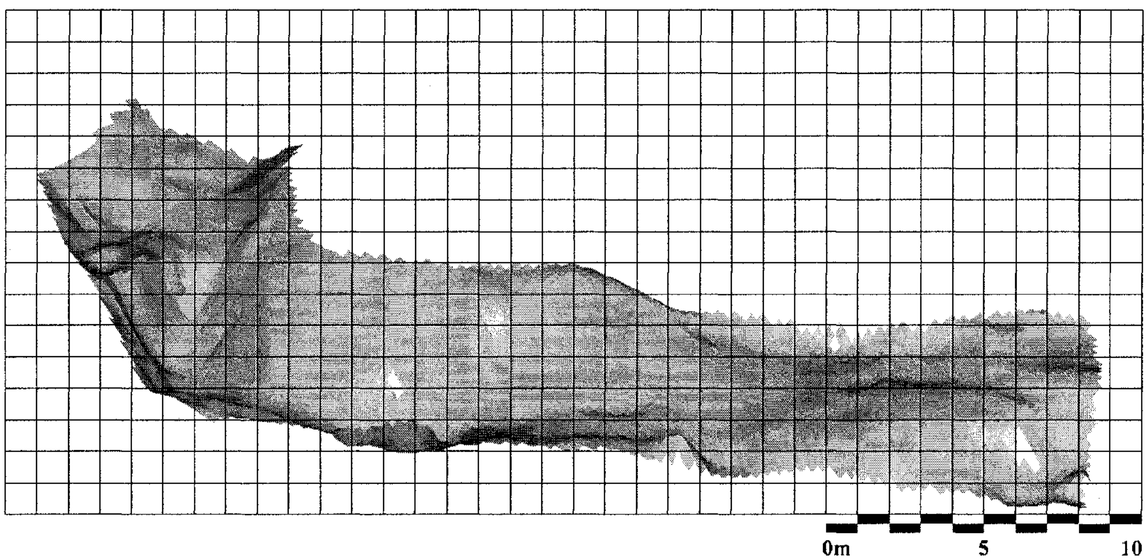

Figure 23: Forfar 1050 1996 Post Summer Flood Shaded Relief Diagram

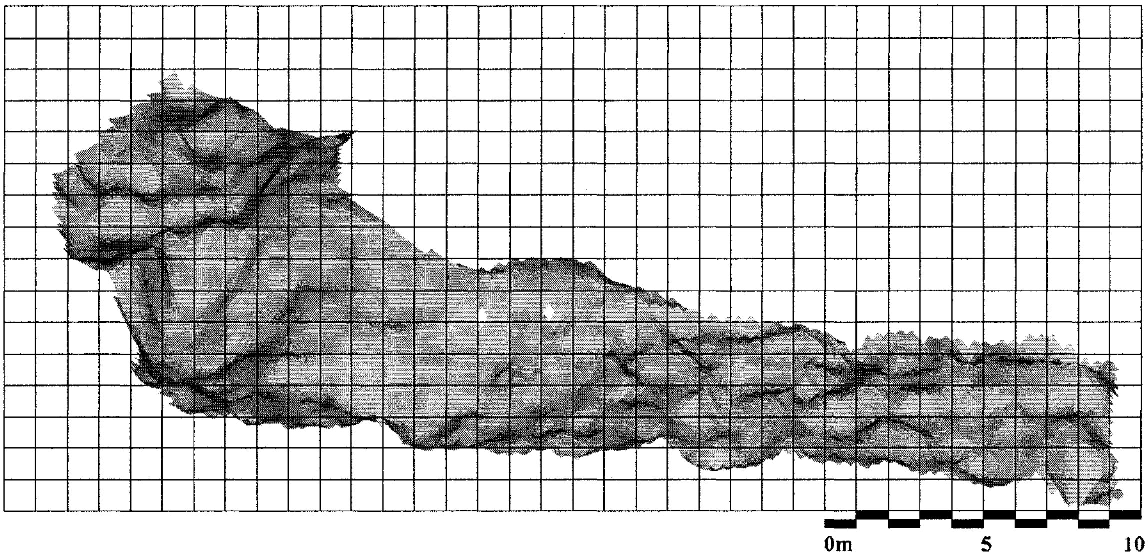

Figure 24: Forfar 1050 1996 Post Spawning Event Shaded Relief Diagram

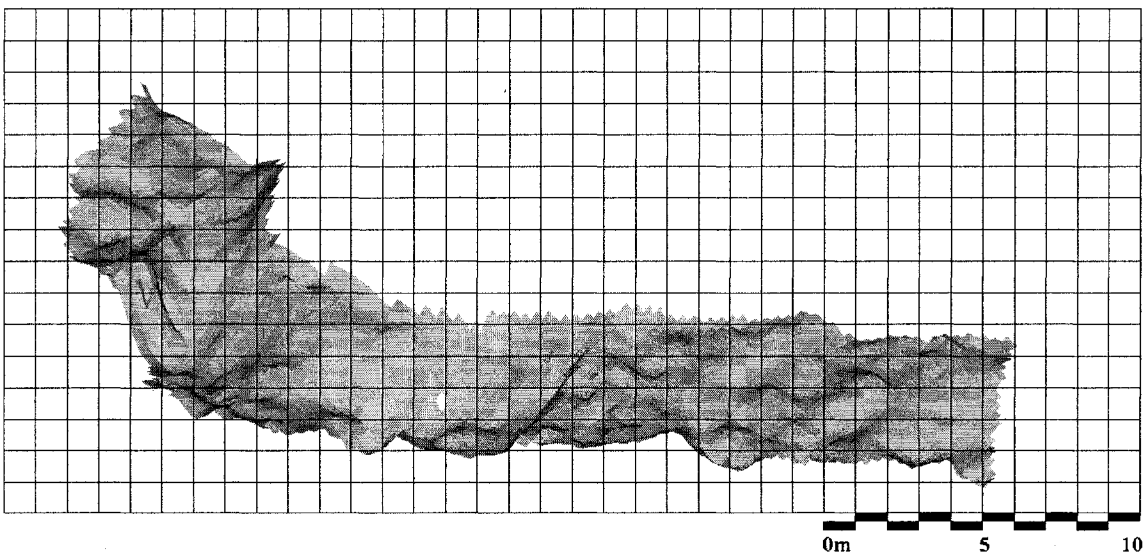

Figure 25: Forfar 1050 1997 Pre Nival Flood Shaded Relief Diagram

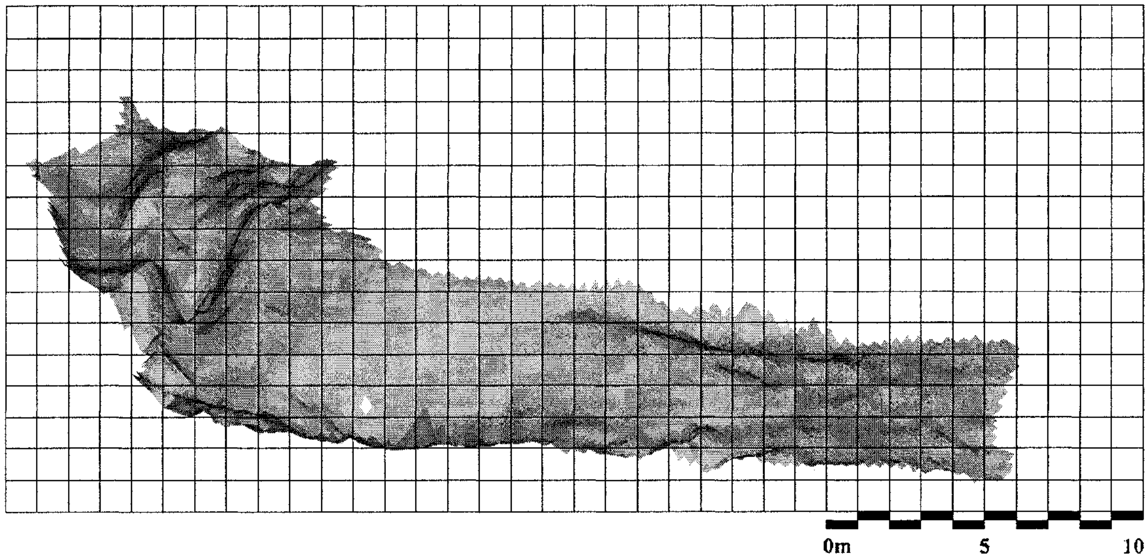

Figure 26: Forfar 1050 1997 Post Nival Flood Shaded Relief Diagram

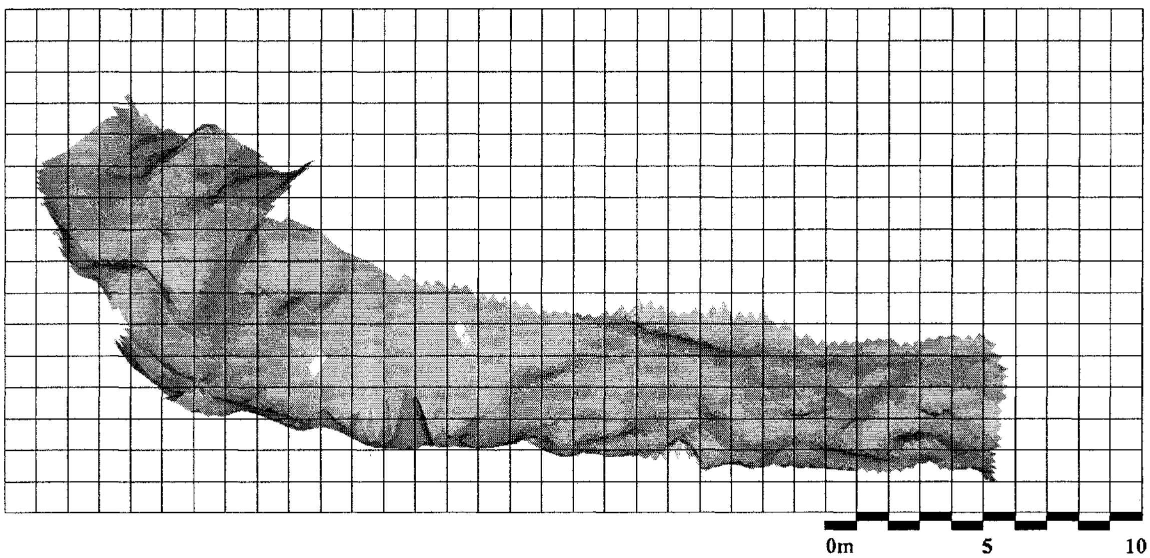

Figure 27: Forfar 1050 1997 Post Spawning Event Shaded Relief Diagram

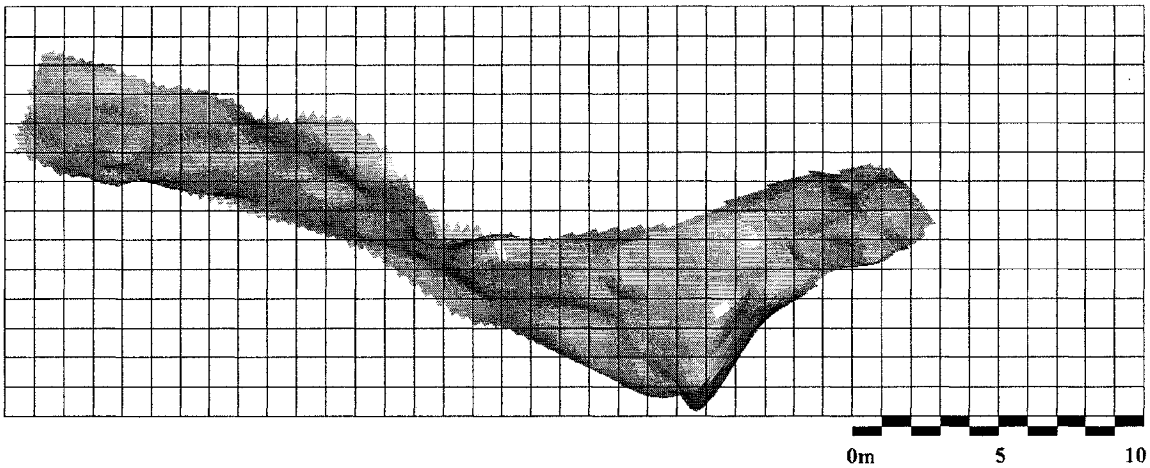

Figure 28: Forfar 1545 1996 Pre Nival Flood Shaded Relief Diagram

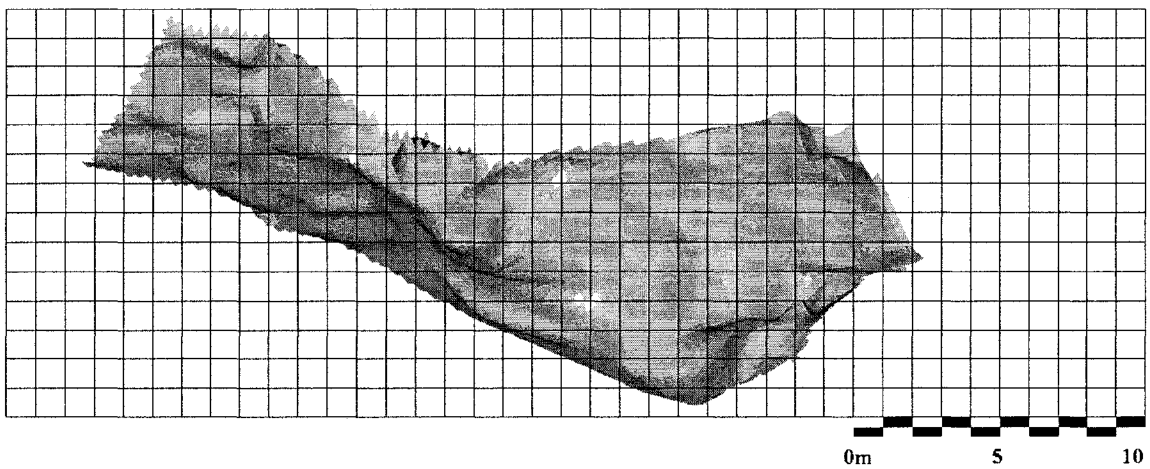

Figure 29: Forfar 1545 1996 Post Nival Flood Shaded Relief Diagram

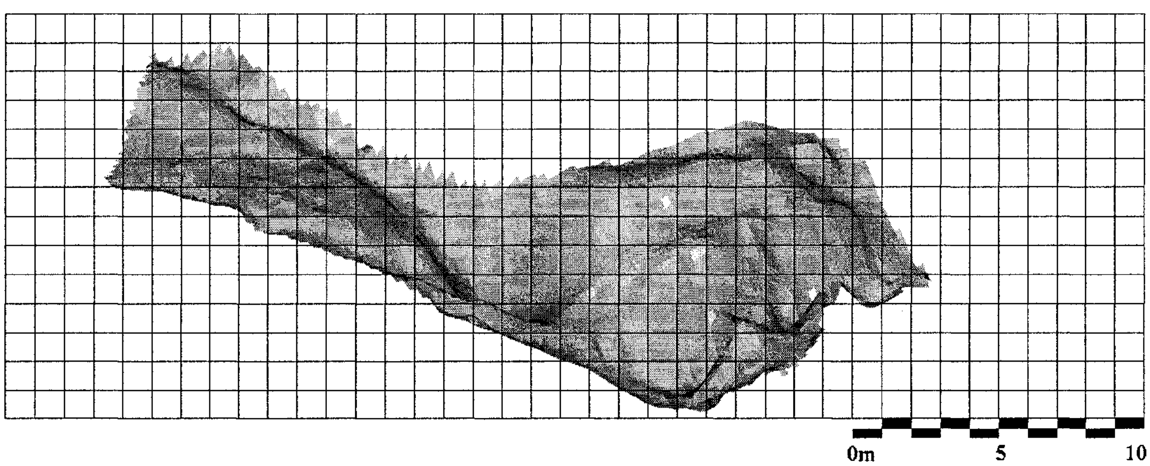

Figure 30: Forfar 1545 1996 Post Summer Flood Shaded Relief Diagram

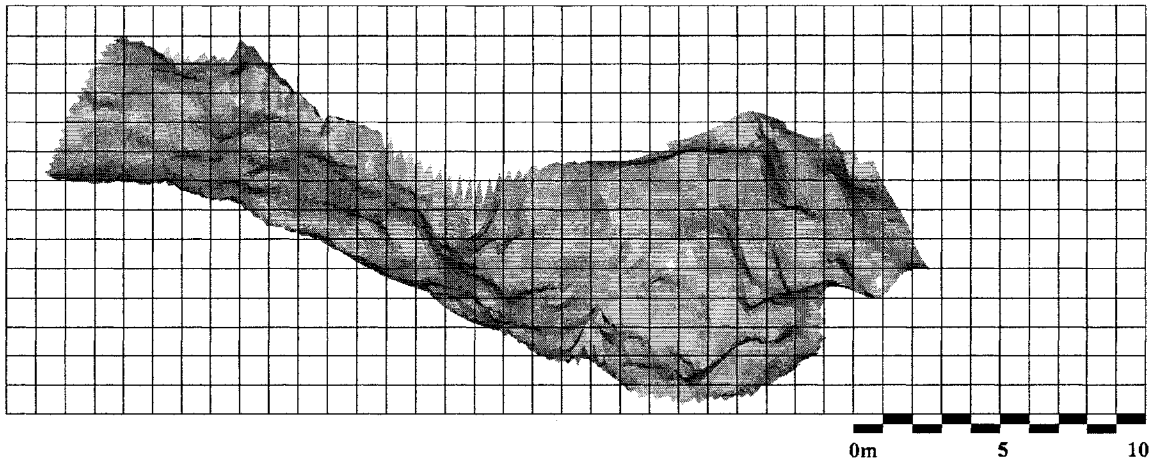

Figure 31: Forfar 1545 1996 Post Spawning Event Shaded Relief Diagram

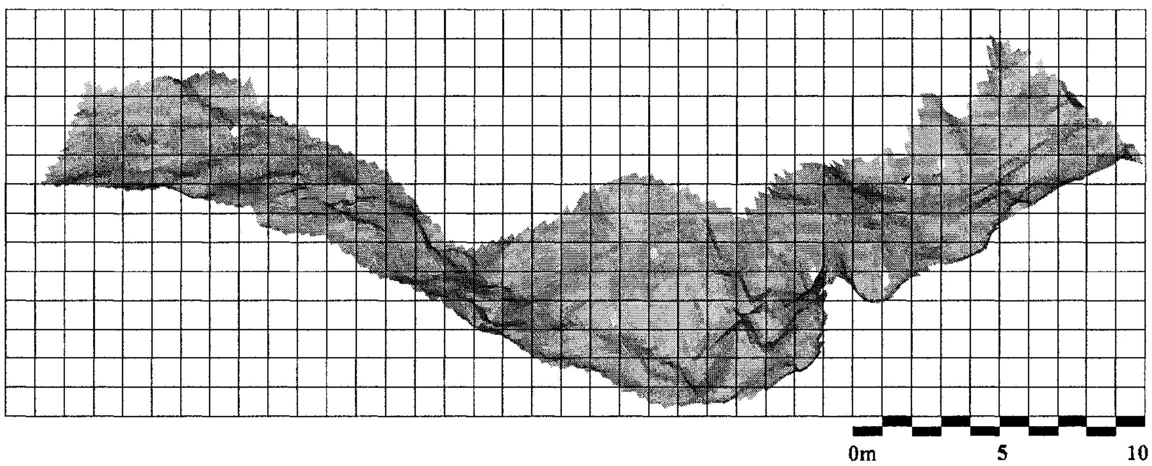

Figure 32: Forfar 1545 1997 Pre Nival Flood Shaded Relief Diagram

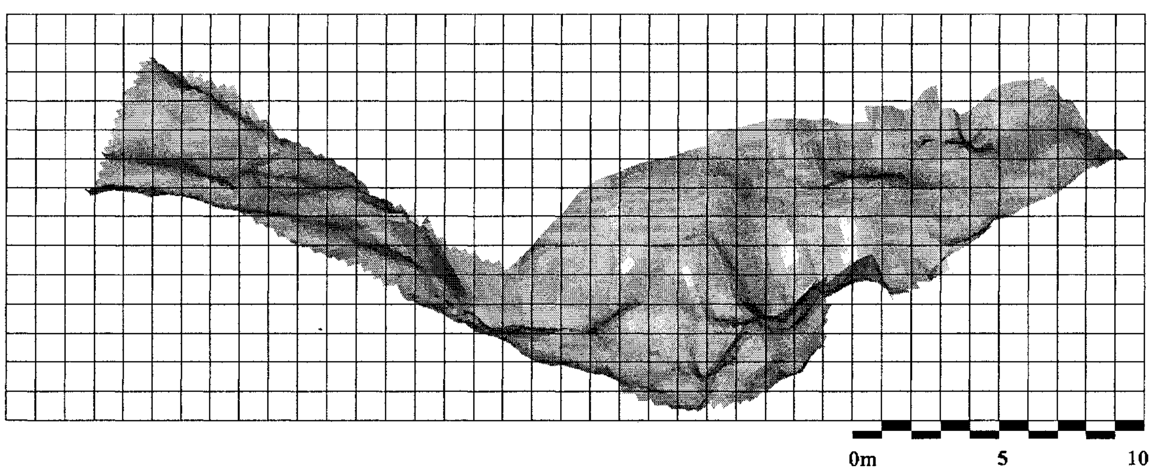

Figure 33: Forfar 1545 1997 Post Nival Flood Shaded Relief Diagram

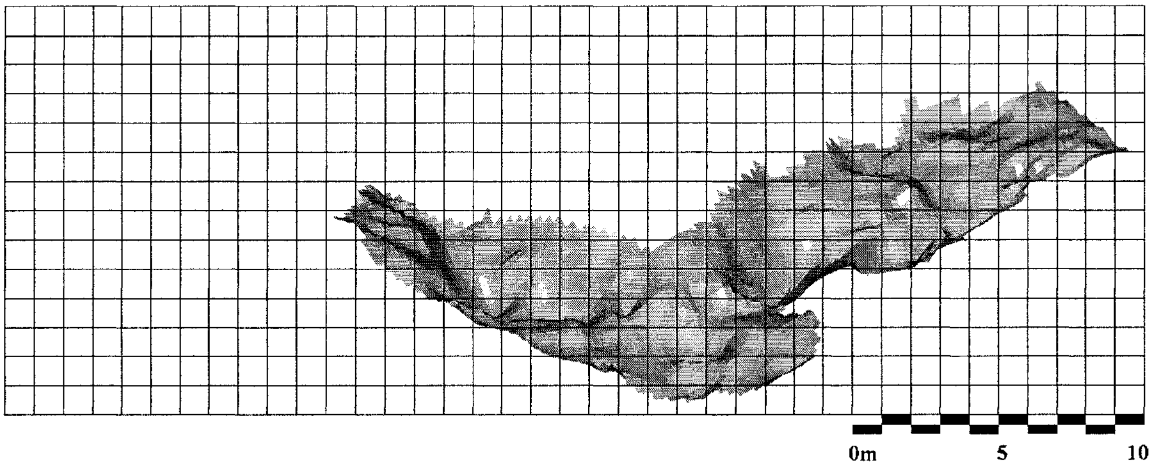

Figure 34: Forfar 1545 1997 Post Spawning Event Shaded Relief Diagram

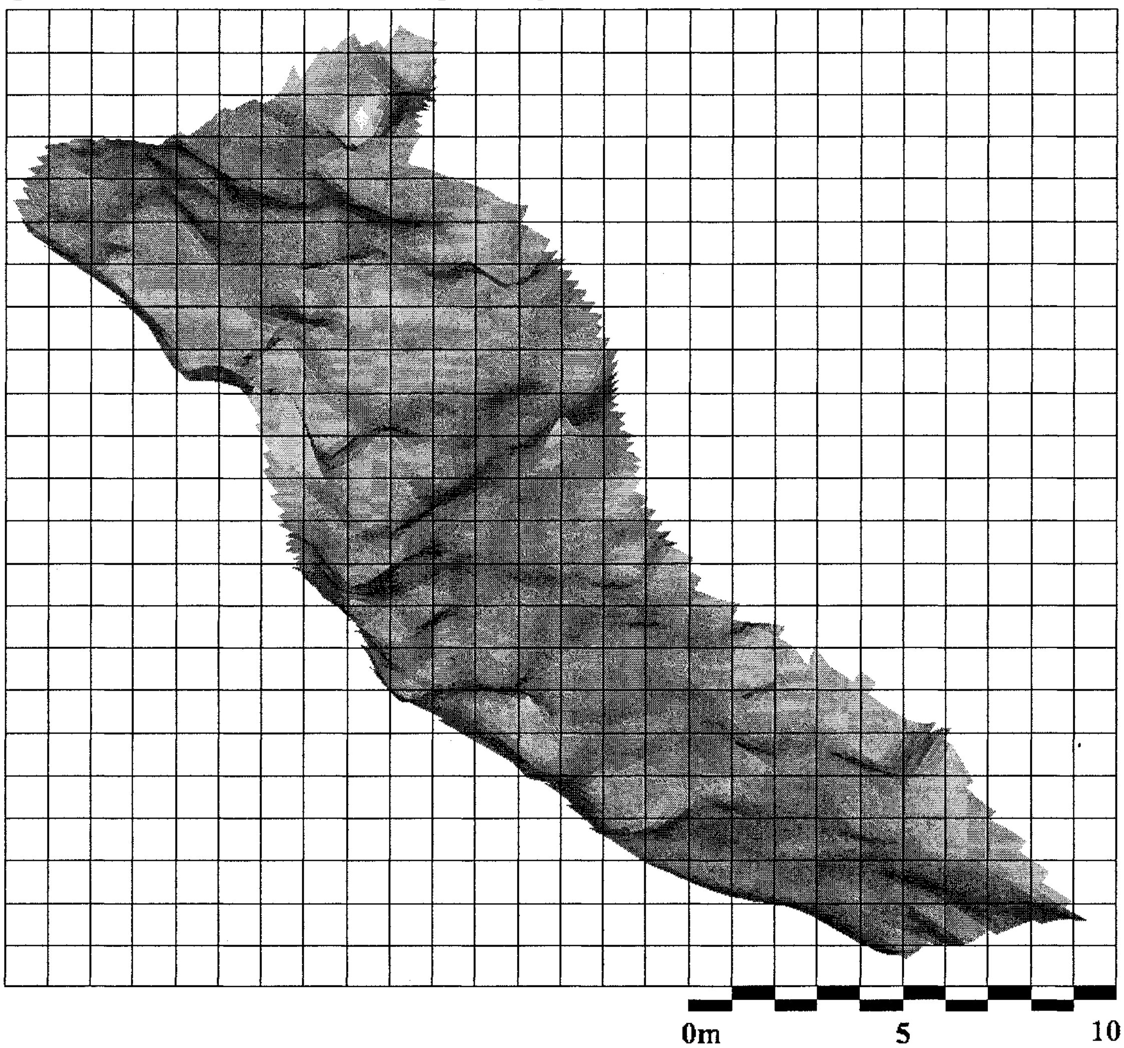

Figure 35: O'Ne-ell 925 1996 Pre Nival Flood Shaded Relief Diagram

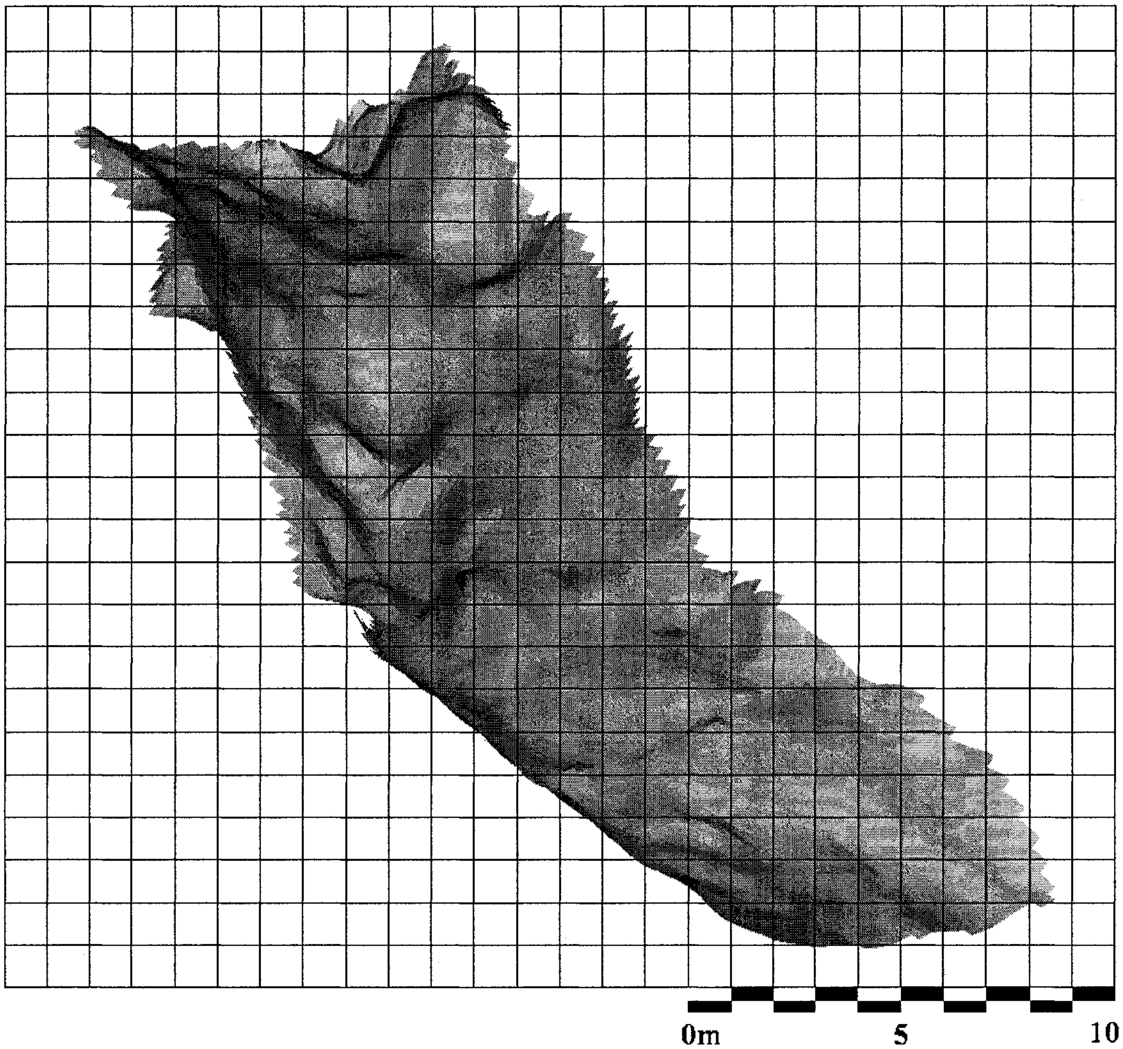

Figure 36: O'Ne-ell 925 1996 Post Nival Flood Shaded Relief Diagram

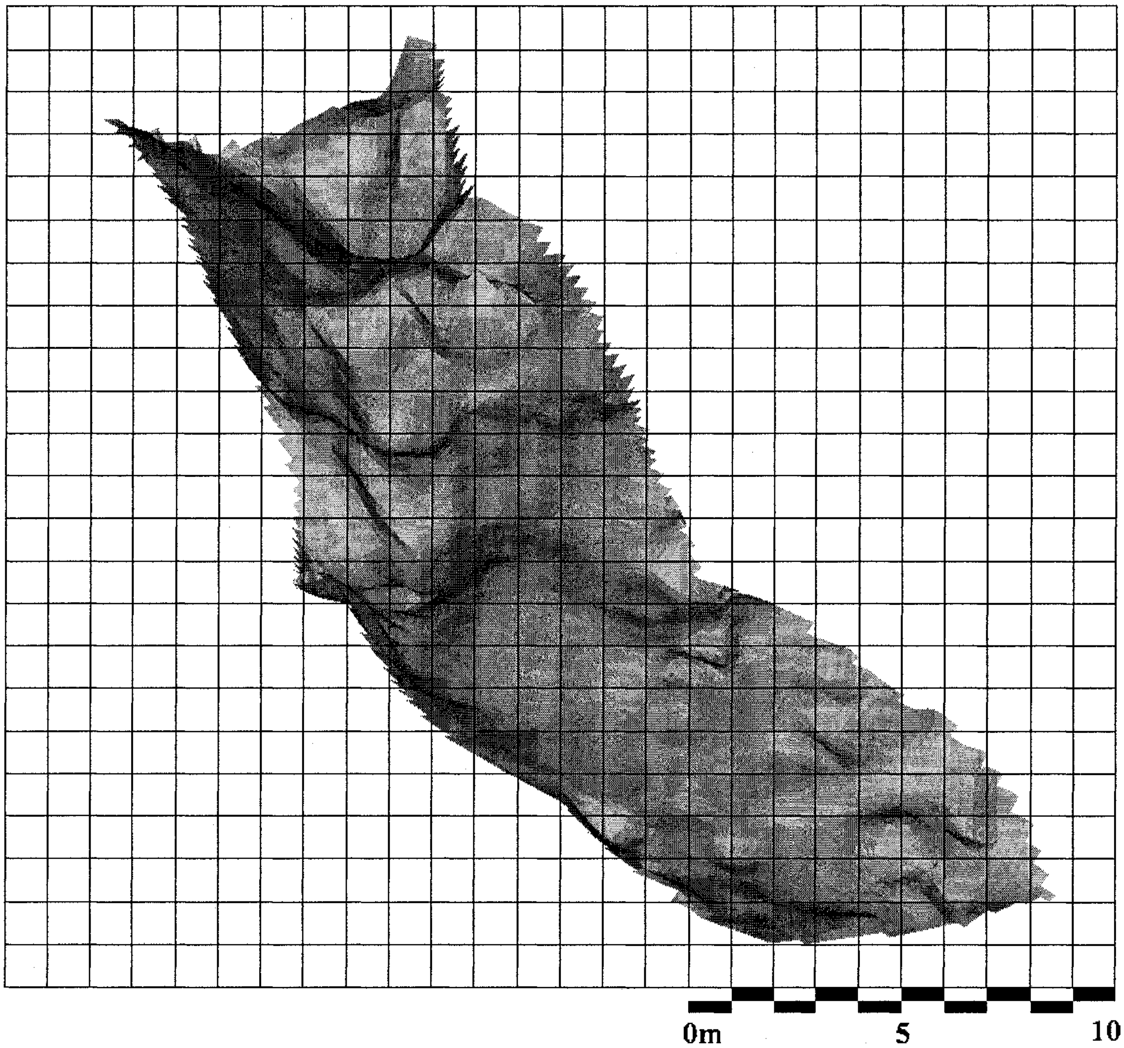

Figure 37: O'Ne-ell 925 1996 Post Summer Flood Shaded Relief Diagram

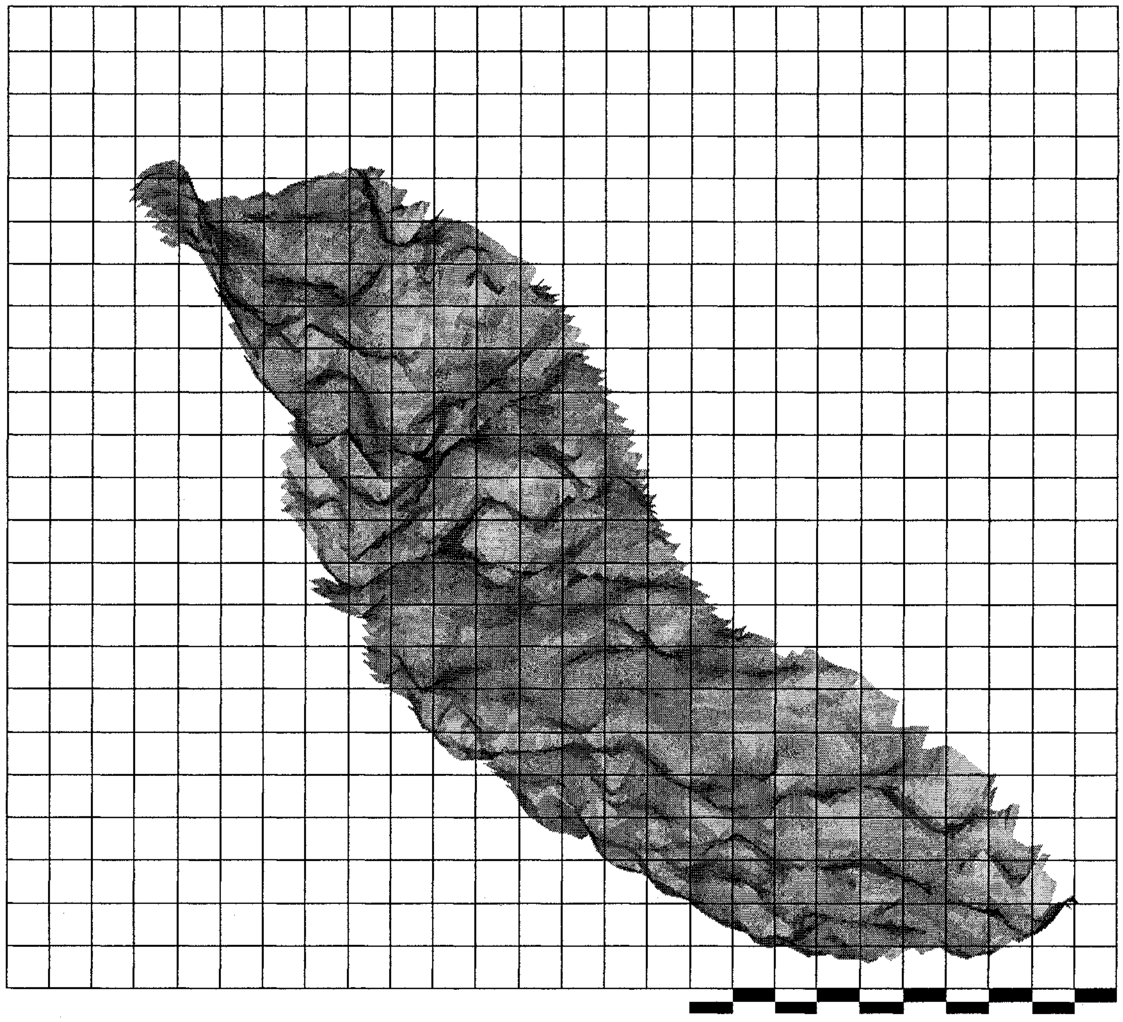

Figure 38: O'Ne-ell 925 1996 Post Spawning Event Shaded Relief Diagram

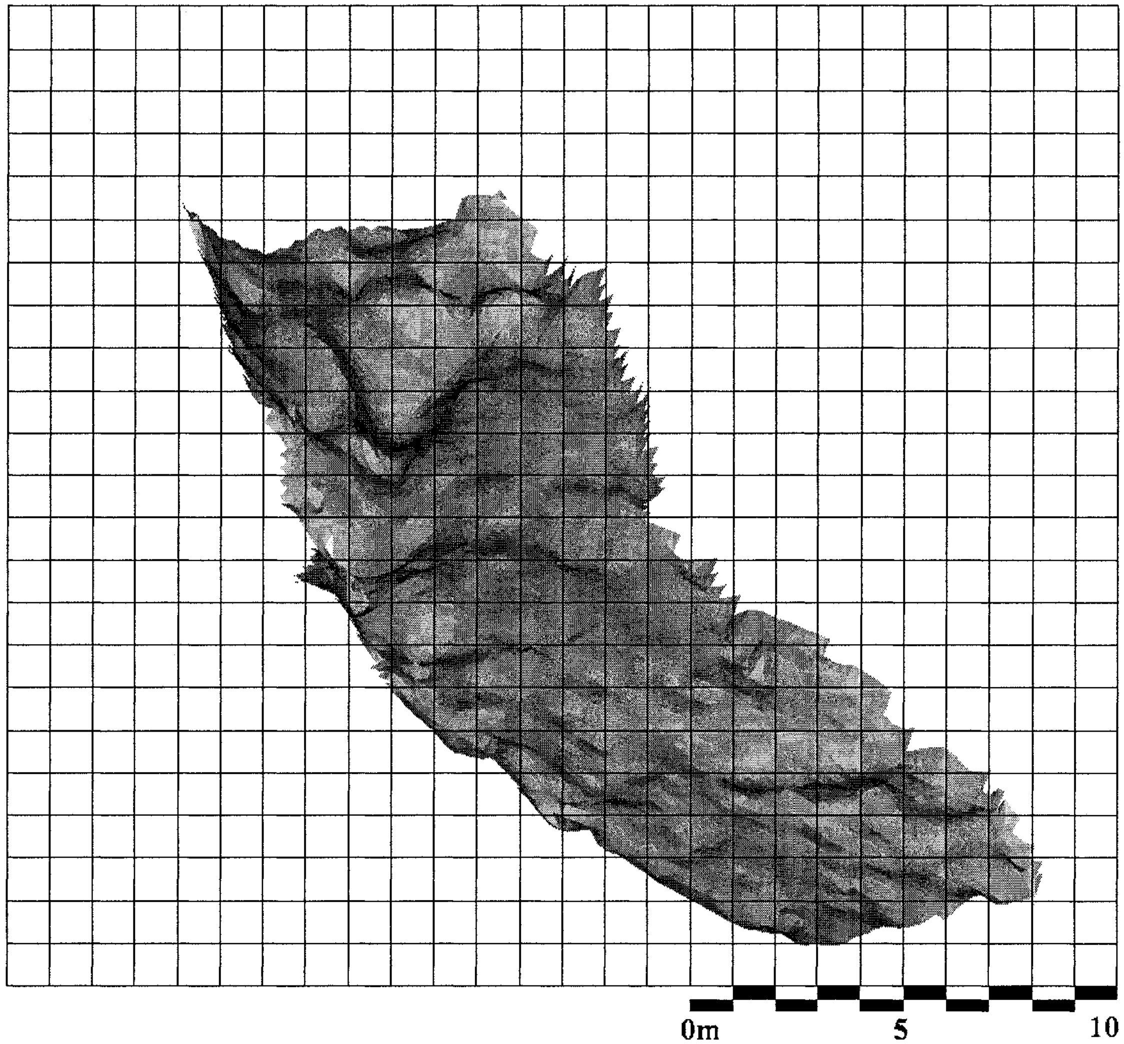

Figure 39: O'Ne-ell 925 1997 Pre Nival Flood Shaded Relief Diagram

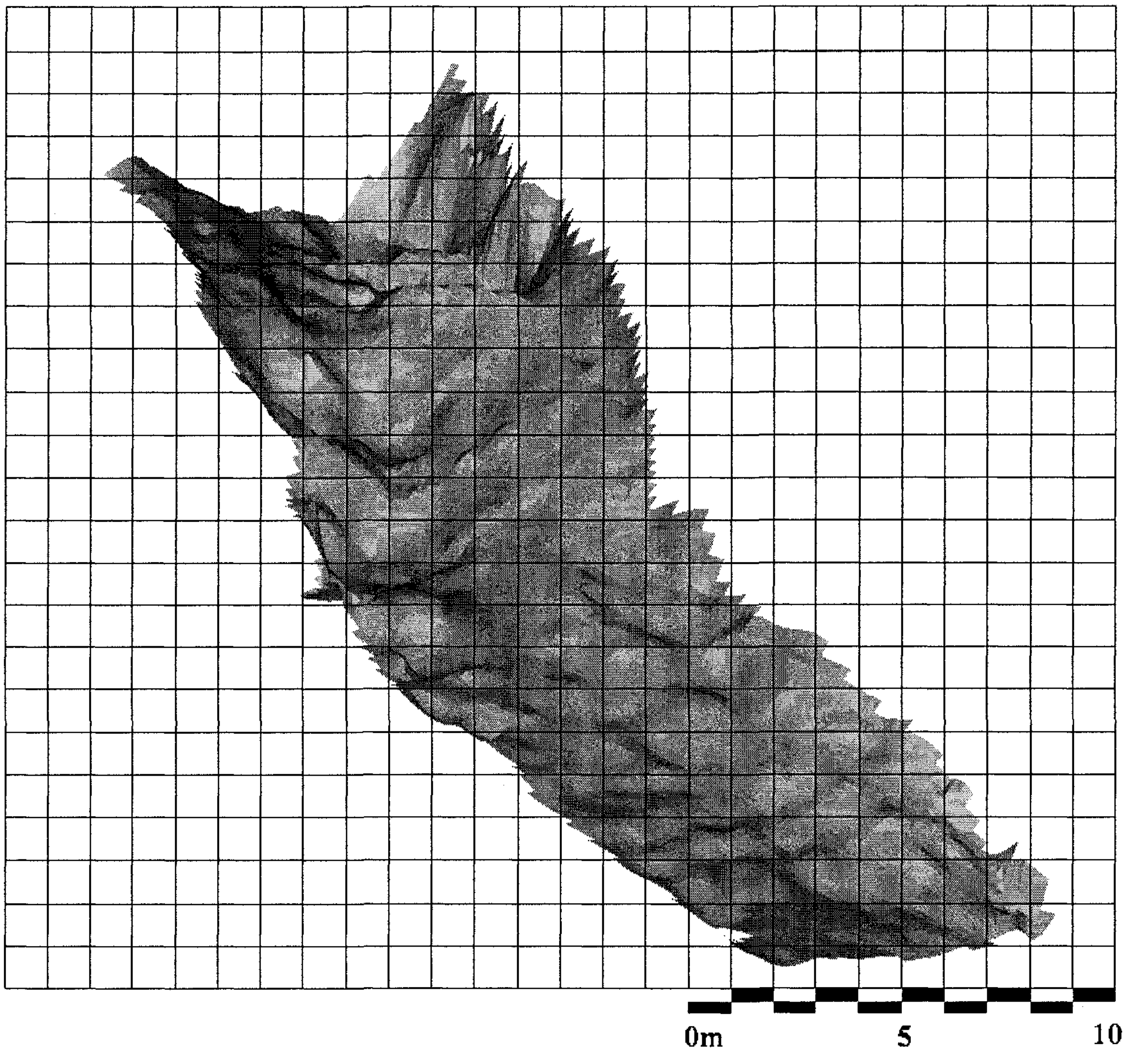

Figure 40: O'Ne-ell 925 1997 Post Nival Flood Shaded Relief Diagram

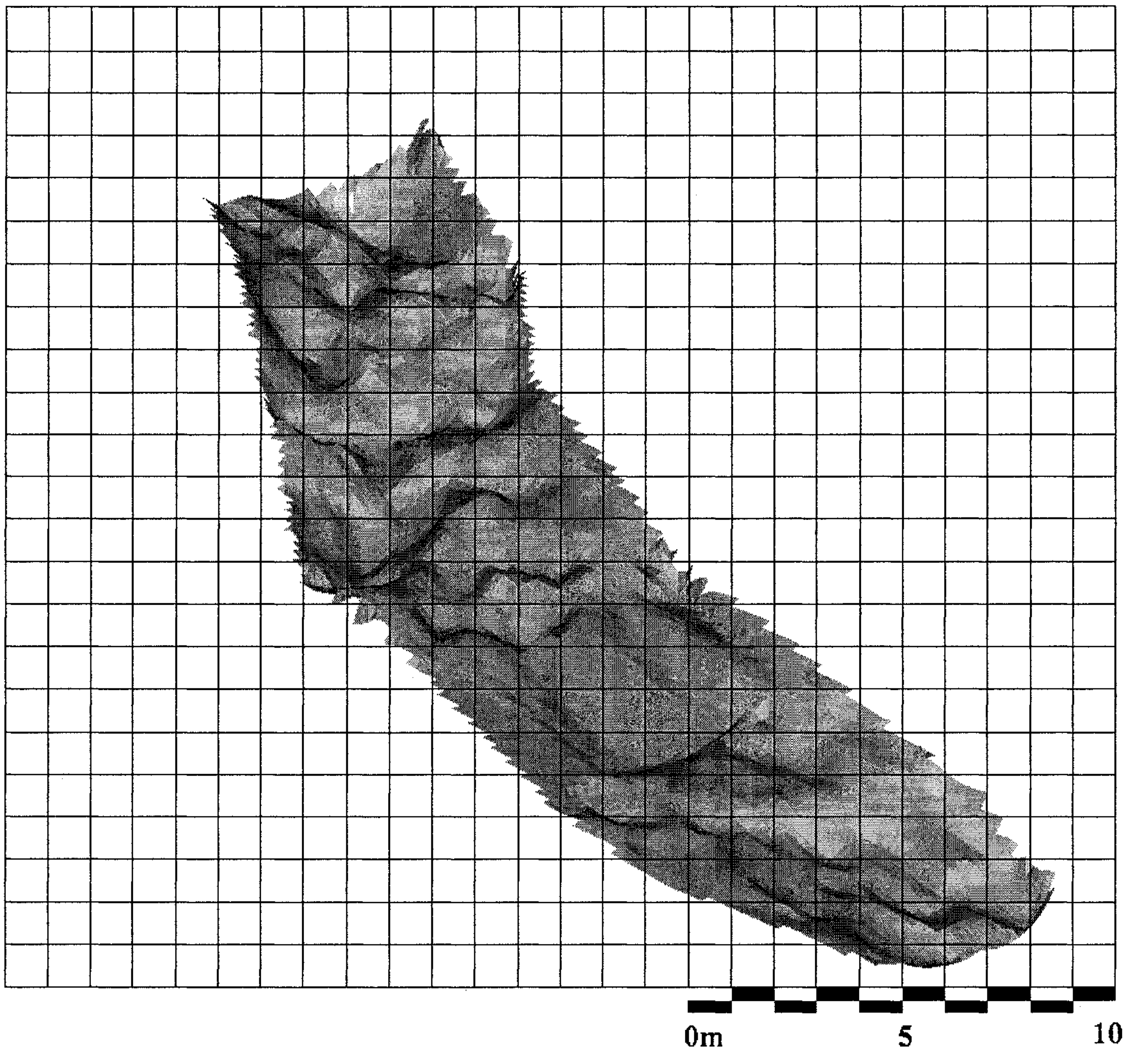

Figure 41: O'Ne-ell 925 1997 Post Spawning Event Shaded Relief Diagram

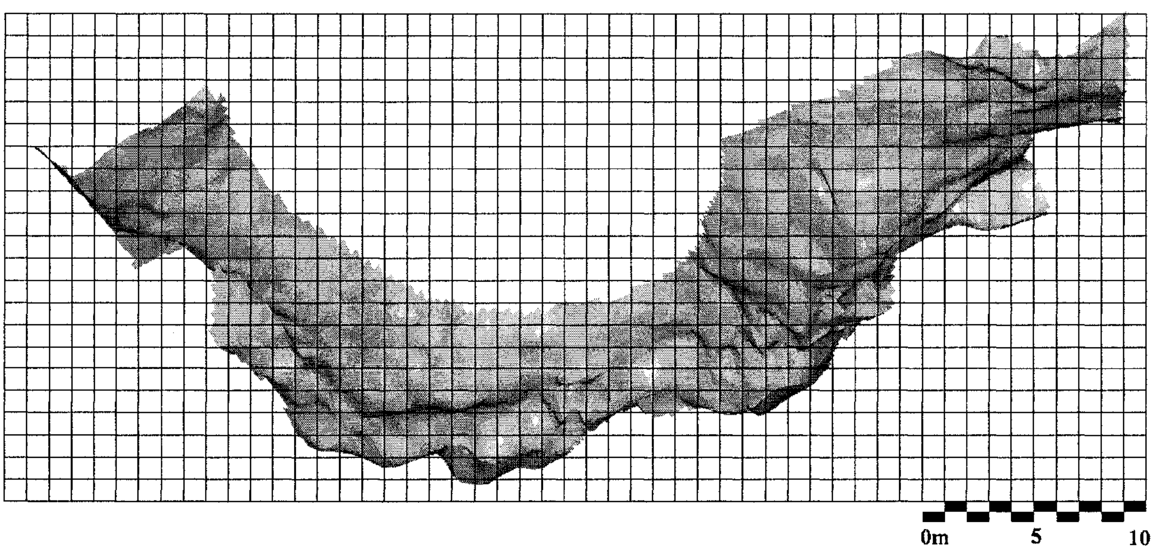

Figure 42: O'Ne-ell 1550 1996 Pre Nival Flood Shaded Relief Diagram

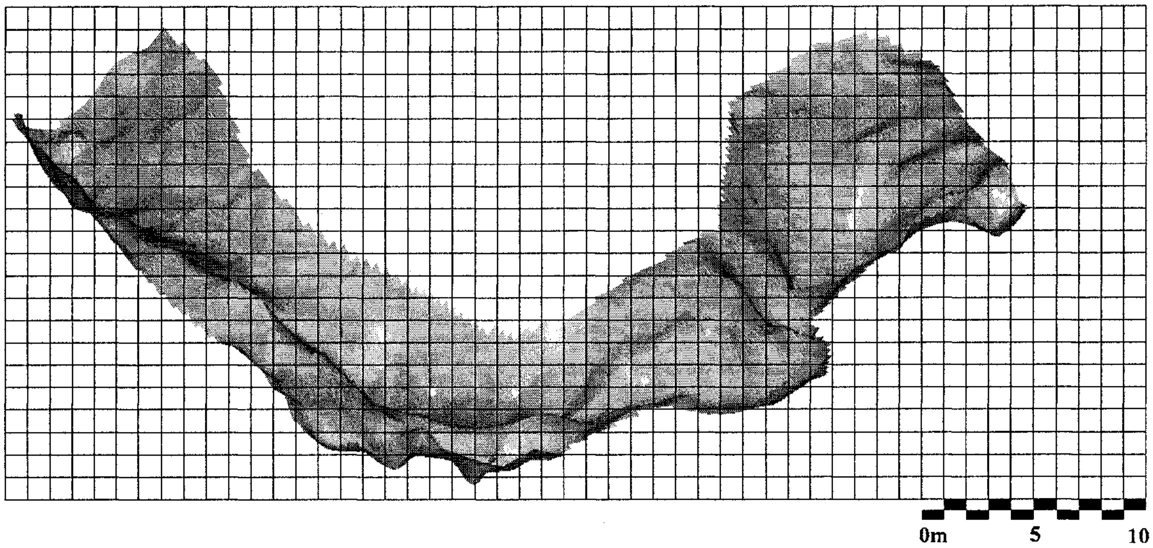

Figure 43: O'Ne-ell 1550 1996 Post Nival Flood Shaded Relief Diagram

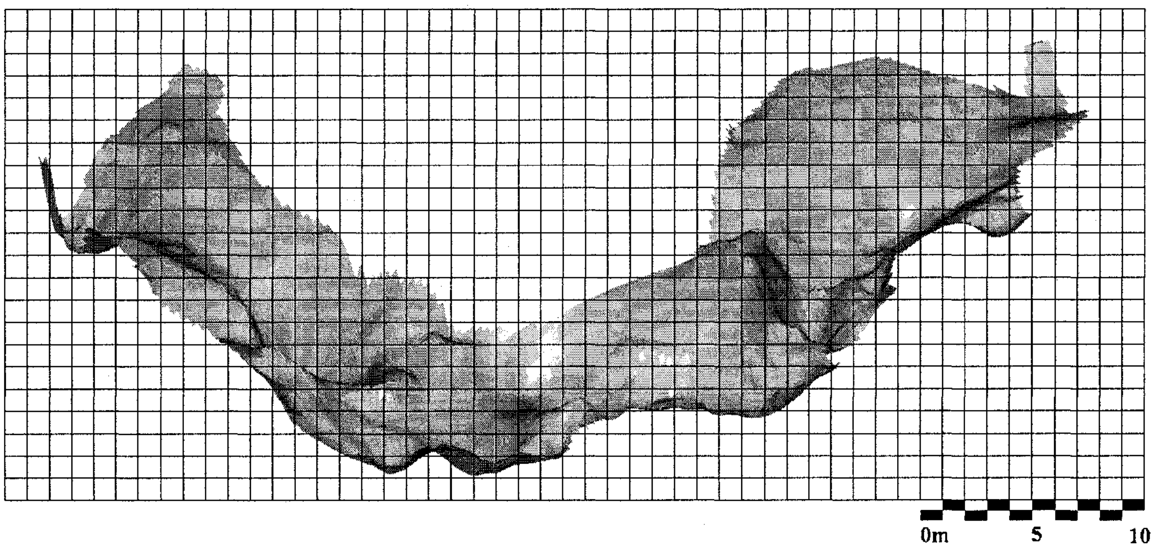

Figure 44: O'Ne-ell 1550 1996 Post Summer Flood Shaded Relief Diagram

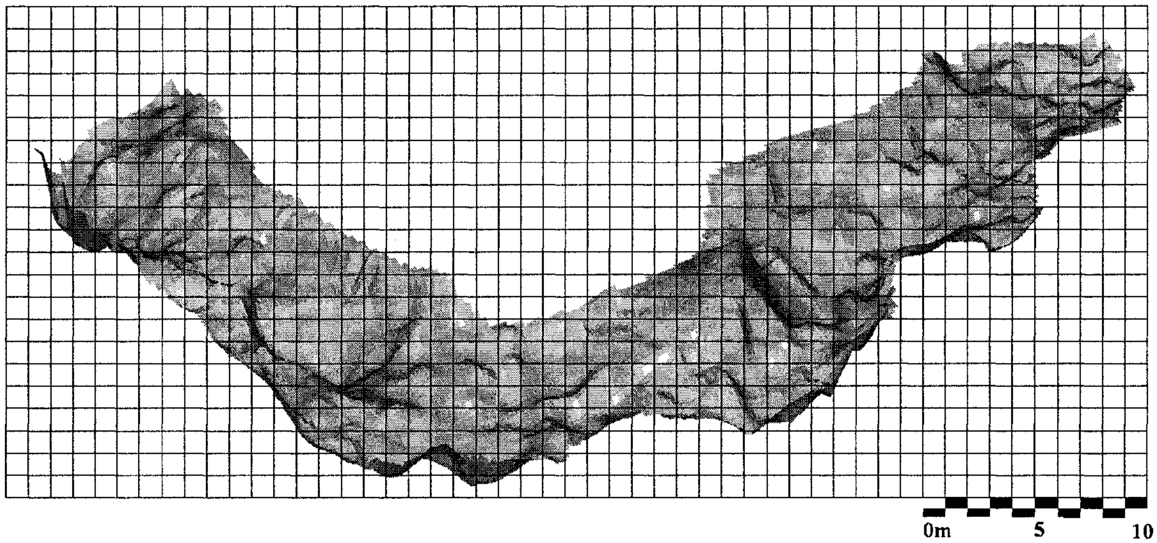

Figure 45: O'Ne-ell 1550 1996 Post Spawning Event Shaded Relief Diagram

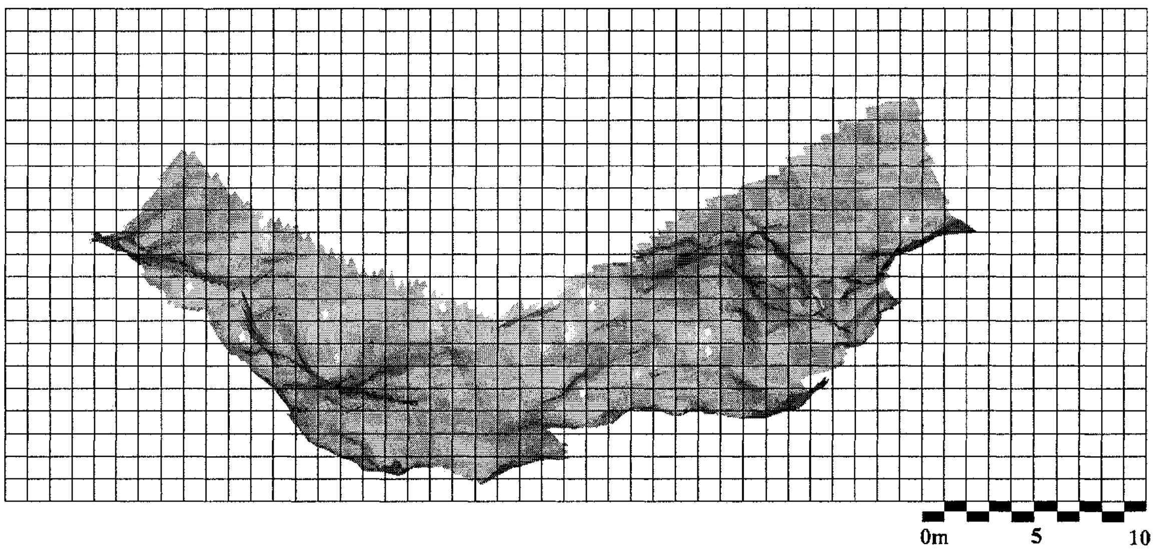

Figure 46: O'Ne-ell 1550 1997 Pre Nival Flood Shaded Relief Diagram

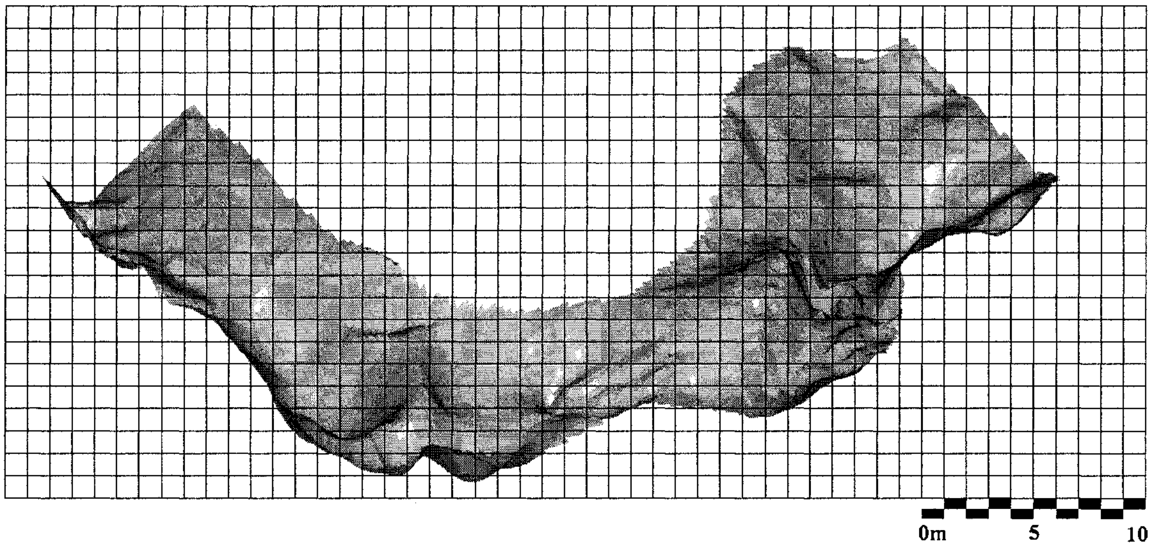

Figure 47: O'Ne-ell 1550 1997 Post Nival Flood Shaded Relief Diagram

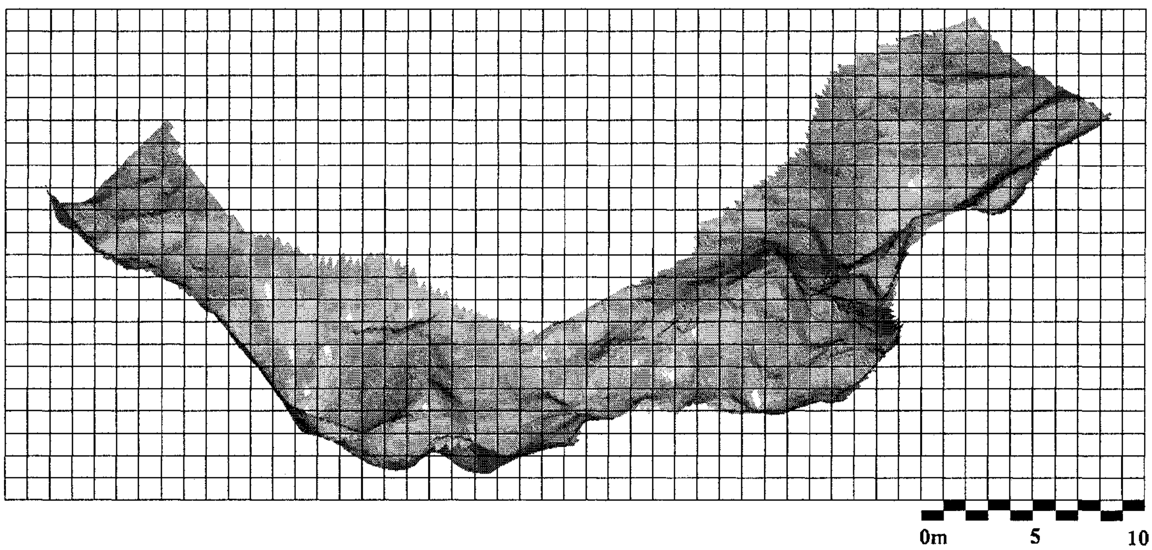

Figure 48: O'Ne-ell 1550 1997 Post Spawning Event Shaded Relief Diagram

4.3 Volume Calculations

4.3.1 Introduction

In a specific stream reach, bed load material is moved downstream by flows, such that material is received from upstream sections and the bed load is discharged out of the reach. A stream section can be in an aggrading (filling), erosional (cutting), or an equilibrium (balanced) state. When considering a pool-riffle sequence in a stream, flood conditions can be eroding the pool site and depositing the material immediately on the downstream riffle. During floods, pool sections are generally erosional sites while gravel bar and riffles are depositional sites. Sear (1996) found that in general, particles in pools tended to have a lower critical threshold of transport than particles on riffles. He attributed this phenomenon to the riffle surface being constantly subjected to chaotic flow resulting in the riffle streambed surface being packed and interlocked resulting in a higher level of imbrication than in pools. However, during a given flood it is entirely possible for net deposition to take place in a pool area and net erosion to occur on gravel bars. By evaluating the stream changes in terms of its aggrading and erosional sections, information may be gathered on the extent (aerial) and magnitude (depths) of changes within the stream reach under study.

By surveying the streambed surface prior to and following a bed load movement event, the volumetric changes for that particular event can be calculated by taking the difference of the pre and post triangular irregular network (TIN) surface models. The volume changes for bioturbation and flood-related events are calculated to compare the effects of both agents on the streambed. These alterations represent the amount of change that occurred within the stream reach under study due to each process. The resulting bed load volume change is reported in terms of fill (aggraded) and cut (eroded) material.

The volumetric calculations are presented using three distinct methods; the total bedload volumes and the unit area bedload volumes and the net unit volumes. The total bedload volumes represent the total work that was performed on the stream and is a surrogate for the power of the stream. The unit area bedload volume uses the average of the cut and fill volumes to describe the changes that occurred on the stream. The cut and fill volumes are assumed to have an equal weighting on the stream morphology in that a stream section can have an episode of aggradation or erosion with each process being equally likely to occur. The net unit volumes identify which of the processes dominated during the episodic event, addressing the question of whether the stream section under study was aggrading or eroding. The following section discusses the results of these calculations for the five-stream sections.

4.3.2 Stream Section Size Variations

The stream reaches studied are long enough to incorporate several deposition and erosional sites as they exhibit pool-riffle morphology. The development of pool-riffle morphology, in a stream, is dependent on the stream gradient, the size and amount of bed load and the occurrence of immobile barriers such as logs and rock outcrops (forced pool-riffle morphology, Montgomery et al. 1995).

Measured stream sections with lower stream gradient and smaller bedload clasts tend to have closer spacing of pool-riffle sequence. Therefore surveyed stream reaches near the mouths of the streams tended to be shorter than those of higher gradient sections. In some cases gravel bars were snow covered for the May pre nival survey. Those areas could not be successfully surveyed and therefore resulted in narrower stream sections than that of summer sections. But for all within reach event comparisons, the stream length used for volume calculations was held constant. The volume data presented as total volume moved in the surveyed reach, and as volume moved per square meter, are measures that simplify comparison between reaches.

4.3.3 Total Bedload Volumes

The calculated volumes of cut and fill are reported in Table 5 for all stream sections including nival floods, summer floods and spawning bioturbation for the two years of the study. The column showing the average volumes represents the arithmetic average of the cuts and fills which reflects the average bedload moved occurring during the event over the stream section surveyed.

The value of average bedload moved for each individual stream reach are of similar magnitude for the flood effects of the 1996 spring flood, the 1996 summer flood and 1997 spring flood (Table 5). This appears to hold for all stream sections under study. Since the area of the stream survey varied in different reaches and to lesser extent in different surveys, the calculated volume for each stream section cannot be compared directly. To compare the different stream sections, the cut and fill volumes were divided by the plan area to obtain a volume per unit area. This method is termed the unit area volume and is used to compare the stream changes from reach to reach.

Date	Forfar 250			Forfar 1050			Forfar 1545		
	Cut m^3	Fill m^3	Average m^3	Cut m^3	Fill m^3	Average m^3	Cut m^3	Fill m^3	Average m^3
Nival 96	5.11	3.02	4.07	2.47	9.32	5.90	5.72	9.41	7.56
Flood 96	4.79	7.58	6.19	5.48	10.10	7.79	18.28	15.21	16.75
Nival 97	1.38	7.85	4.62	9.97	8.78	9.38	16.24	6.74	11.49
Spawning 96	11.35	3.01	7.18	7.75	7.30	7.53	7.99	12.12	10.05
Spawning 97	7.06	2.61	4.84	2.03	8.10	5.07	0.19	4.03	2.11

Date	O'Ne-ell 925			O'Ne-ell 1550		
	Cut m^3	Fill m^3	Average m^3	Cut m^3	Fill m^3	Average m^3
Nival 96	24.58	7.06	15.82	34.66	27.09	30.88
Flood 96	13.77	4.62	9.20	41.94	56.15	49.05
Nival 97	21.47	2.97	12.22	36.04	28.10	32.07
Spawning 96	12.88	9.53	11.21	40.61	20.40	30.51
Spawning 97	5.74	6.37	6.06	28.34	16.95	22.65

Table 5: Total Calculated Bed Load Volumes

4.3.4 Unit Area Bedload Volumes

The unit area volumes are calculated by dividing the cuts and fill volumes by the total surface area of the surface model. Dimensionally the resulting quotient is meters, which can be thought of as the average depth of change. The resulting quantities are then compared for bioturbation and flood events to determine if both processes are comparable in magnitude. Table 6 is a summary table for the results of these calculations. The two processes have been separated to demonstrate the effect of each. For the most part, the flood event response for each stream section exhibits average cut and fill depths that are similar in magnitude with low standard deviations. The average of the cut and fill depths for the sockeye spawning show a consistent reduction in the 1997 year from the 1996 spawning year.

Date	**Forfar 250** m^3/m^2			**Coefficient of Variation**	**Forfar 1050** m^3/m^2			**Coefficient of Variation**	**Forfar 1545** m^3/m^2			**Coefficient of Variation**
	Cut	Fill	Avg.	%	Cut	Fill	Avg.	%	Cut	Fill	Avg.	%
Nival 96	0.030	0.018	0.024		0.015	0.058	0.037		0.033	0.054	0.044	
Flood 96	0.025	0.040	0.032		0.020	0.036	0.028		0.084	0.070	0.077	
Nival 97	0.008	0.047	0.028		0.041	0.036	0.039		0.071	0.029	0.050	
Average			0.028	15.0			0.034	16.4			0.057	30.7
Spawning 96	0.059	0.016	0.038		0.029	0.027	0.028		0.036	0.055	0.046	
Spawning 97	0.042	0.015	0.029		0.008	0.032	0.020		0.001	0.024	0.013	
Average			0.033	13.4			0.024	17.2			0.029	56.4

Date	**O'Ne-ell 925** m^3/m^2			**Coefficient of Variation**	**O'Ne-ell 1550** m^3/m^2			**Coefficient of Variation**
	Cut	Fill	Avg.	%	Cut	Fill	Avg.	%
Nival 96	0.073	0.021	0.047		0.070	0.055	0.062	
Flood 96	0.041	0.014	0.028		0.054	0.072	0.063	
Nival 97	0.075	0.010	0.043		0.086	0.067	0.077	
Average			0.039	26.1			0.067	12.2
Spawning 96	0.043	0.031	0.037		0.079	0.040	0.060	
Spawning 97	0.021	0.023	0.022		0.063	0.037	0.050	
Average			0.029	26.1			0.055	8.8

Table 6: Unit Bed Load Volumes

Assuming that the system is in static equilibrium, the net depth of change is expected to be zero. To assess if the stream section was in an aggradational or erosional state, the infilling (fill) was given a positive value while erosion was given a negative value. A deviation from this value implies that the stream section is aggrading or eroding during the time period or that the time duration is too small to achieve local equilibrium. The results of the difference are shown in Table 7.

Date	Forfar 250 m^3/m^2	Forfar 1050 m^3/m^2	Forfar 1545 m^3/m^2	O'Ne-ell 925 m^3/m^2	O'Ne-ell 1550 m^3/m^2
Gradient (%)	0.50	0.90	1.70	0.55	0.50
Nival 96	-0.012	0.043	0.021	-0.052	-0.015
Flood 96	0.015	0.016	-0.014	-0.027	0.018
Nival 97	0.039	-0.005	-0.042	-0.065	-0.019
Spawning 96	-0.043	-0.002	0.019	-0.012	-0.039
Spawning 97	-0.027	0.024	0.023	0.002	-0.026

Table 7: Net Unit Volumes

The net changes from flood related events are not extreme as evidence by the range of values from +0.043m to -0.065m. Note that the maximum depth of change is approximately equivalent to the "b-axis" length of the gravels (Table 2). In evaluating the change due to flood for all of the reaches, it is apparent that O'Ne-ell 925 is the only stream reach that consistently erodes. All of the other stream reaches fluctuate between aggradation (positive values) and erosion (negative values). Flood erosion depths, noted as unit bedload cuts (Table 6), appear to increase with increasing gradient for both Forfar and O'Ne-ell Creek. As well as showing large cut volumes, the higher stream gradient sites have higher depths of fill or deposition. This relationship with gradient does not appear to hold for bioturbation events.

4.4 Spatial Volume Distribution & Isopach Maps

4.4.1 Introduction

The previous section described how the streambed volumes and depths (volume per unit area) changed in the 1996-1997 sampling period at the five study reaches on Forfar and O'Ne-ell Creeks. Those results quantified the amount of bed load moved within the stream length as well as indicating whether the stream section was eroding or aggrading during an event. However, those results do not show the pattern and distribution of spatial changes over the streambed. A method of describing the patterns of deposition and erosion would assist in delineating the morphological changes resulting from floods and sockeye salmon spawning related transport. To delineate the erosional and depositional patterns of streambed changes, isopach maps are utilized.

Isopach maps are similar to contour maps as they delineate topographical changes in a series of discrete vertical changes but offer a means of displaying the results in a continuous spatial framework. By displaying the spatial model of change over a temporal framework, the streambed patterns of erosion and deposition can be depicted more easily and with greater clarity.

To generate this temporal model, a TIN (triangular irregular network) was used. Using the nival flood event as an example, the post nival flood TIN was subtracted from the pre nival flood TIN. The resulting TIN provided a surface model which, being the difference between the two models, exhibits 3 main areas of changes: positive areas for infilling, negative areas for erosion and areas of zero changes. To further refine the model, the areas of infilling and erosion were categorized into 5 cm increments. By using 5 cm graded increments, the pattern of the vertical change could be evaluated spatially over the streambed.

The isopach maps are presented in plan view and a colourimetric convention was devised to distinguish the deposition and erosion zones. The convention used for the isopach maps is that the red spectrum represents different levels of infilling, the blue spectrum represents the areas of erosion and the gray zones represents the areas of zero changes. A red and blue spectrum, using intermediate colors, has been used to quantitatively represent changes of 0.05m. The resulting surface model is especially useful to allow comparison of the different erosional patterns resulting from flood transport and sockeye spawning related transport.

4.4.2 Nival Flood

The nival flood isopach maps of Forfar 250, 1996 and 1997 (Figures 50 and 53) show sections of infilling alternating downstream with erosional areas. Comparison of the Forfar 250 1996 spawning event (Figure 52), with the following 1997 nival flood (Figure 53) shows that the areas that were filled by redd excavation tended to be eroded, and the areas that were excavated by the redd excavation tended to be filled in by the first flood that occurs after the spawning.

The 1997 Forfar 1050 nival flood (Figure 58) demonstrates a similar erosional pattern to that of 1996 Forfar 1050 spawning surface (Figure 57). The 1997 Forfar 1050 nival flood (Figure 58) shows the extension of a point bar with erosional patterns on the outside section on the bend. The downstream end of the stream section demonstrates the consistent excavation, which might be related to the previous year's infilling. The 1996 Forfar 1545 nival flood (Figure 60) shows regions of alternating infilling and erosion as previously observed in Forfar 250. The 1997 Forfar 1545 nival flood (Figure 63) shows a long distance of excavation with infilling in the lower stream section.

The series of isopach maps at O'Ne-ell 925 (Figures 65-69) show a strong reciprocal pattern in which floods excavate the thalweg, adding material to the bars while spawning bioturbation removes material from the bars and fills the thalweg. Notice that the thalweg in the upstream portion was excavated during all three floods and filled by the two spawning bioturbation events.

At O'Ne-ell 1550 the nival floods of 1996 and 1997 (Figures 70 and 73 respectively) show patterns of erosion and deposition in which the thalwegs are excavated. Notice how the deep pool at the upstream end migrated upstream and towards the right bank over the flood sequence in 1996-97. At this reach as in the others, the nival flood tends to re-establish the thalweg of the stream returning it to the pool-riffle morphology.

4.4.3 Summer Flood

The 1996 summer flood offered the opportunity of demonstrating the effects of multiple flood events on the streambed. Two general patterns emerge from these isopach maps. The first is that the existing thalweg tends to be accentuated with a deepening of the pools and aggradation of the gravel bars. Figure 56, the 1996 Forfar 1050 summer flood, demonstrates further excavation around the middle of the stream section followed by an aggradation downstream.

The second pattern is the excavation of deep scour holes and the deposition of this material a short distance downstream. At O'Ne-ell 1550 (Figure 71), deep scour at the upstream end was followed by aggradation 5-7 m downstream. This can also be observed at Forfar 1545, Figure 61, where excavation of a pool in the middle of the reach is followed by strong aggradation 8-10 m downstream. O'Ne-ell 925 (Figure 66) shows an infilling of the pool with the gravel bars being eroded.

4.4.4 Sockeye Salmon Spawning

The creation of redds accompanying spawning, results in a pattern of erosion and deposition very different from that of floods. Oval pockets of cutting and filling are evident over the entire set of stream sections. This erosional pattern can clearly be observed in the Forfar 1050 1996 spawning event (Figure 57). O'Ne-ell 925 (Figures 67 and 69) also shows this pattern but it appears to be of lower density in this stream section. Notice how the areas of no change (grey) are much higher in the 1997 spawning isopach than in 1996. This does not imply that the stream areas were not changed by the fish but rather that the resulting stream surface after the salmon redd excavation exhibited smaller net vertical change.

Another pattern that emerges from the isopach diagrams is that the riffles are the preferred areas of salmon spawning. An infilling of the pools occurs as the excavated material rolls downstream. This effect is not so pronounced in the lower stream sections such as Forfar 250. This is probably due to the fact that the higher stream sections tend to have a higher stream power resulting in deeper pools. The effects of the salmon spawning on the stream tend to be more localized than those from flood events. This reflects the different processes of erosion.

The morphological pattern of floods and sockeye salmon spawning over the streambed have now been visually described using the isopach diagrams, but these data can be used to address the question: What are the percentages of change for deposition, erosion and zero units? The following section will describe the distribution of change for each topographic unit for both processes.

4.4.5 Effective Depth of Change – Isopach Maps Volumes

The figures in the previous section represented the depth of change over the streambed in 5 cm increments. The selection of the 5 cm increment was arrived at by accounting for the measurement error as well as the minimum size of the bed material in these streams. To select the vertical increment to use in the calculation of volumes, the reported error of 1cm was initially used (see section 3.4.1). By calculating the volumes into 1cm increments, it was possible to account for the possible measurement error in both the deposition and erosion volume calculations. The first one centimeter volume calculation was grouped into the zero change category (Figure 49). The reported zero change then represents the change in volume contained within 1cm (± 1cm) allowing for settling and trampling as reported earlier. The total acceptable error was the set at 2cm, which is approximately double the reported error.

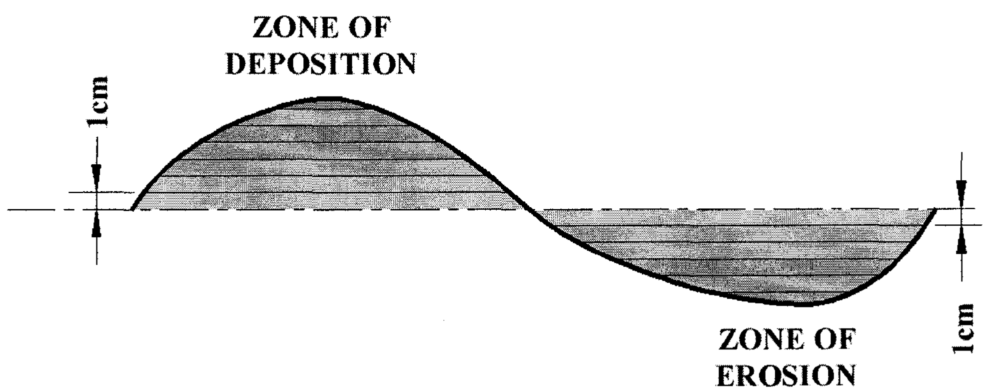

Figure 49: Diagrammatic Representation of the Increments Method

To properly reflect the size of bedload material in the stream, a vertical increment was required. Gottesfeld's (1998) magnetic tracer study provided a mean of making an estimate of the vertical increment (Table 2). Using the smallest of the measured clast axes (the "C" axis), the minimum average clast thickness for all the stream sections is 4.18cm. It was decided that the 1 cm interval volume calculations be combined into 5cm groupings to identify the deposition and erosion zones. As previously described, the zero change consisted of the first centimeter (±) in the deposition and erosion zone.

The volumes in Table 8,9,10 (nival floods, summer flood and redd excavation respectively) are reported as percentages of the total bedload moved for that event. To delineate between deposition and erosion, the deposition depths of change are reported as positive and the erosion depths of change are reported as negative.

Table 8 compares the percentage of change for each elevation increment for the 1996 and 1997 nival floods. In example, for Forfar 1050, the percentage of zero change in 1996 is

13.5% while the zero change in 1997 is 12.1%, resulting in a difference of 1.4%. The difference in the zero percentage results for all the other stream sections in both years are found to be similar, except for Forfar 250, which has a much higher difference, of 14%, between 1996 and 1997. In 1997, at Forfar 250, it is found that 78% of the bed material is infilling within a 10cm depth (Table 8). Referring back to Figure 52, this appears to correspond well with the isopach map. This is a good example of a stream section in aggrading stage.

The group averaged zero percent change for the 1996 nival flood is 11.8% while the group averaged zero percent change is 8.70% in 1997. Interestingly, the 1997 peak springmelt streamflows were greater than those in 1996 (6.54 m^3/s and 5.94 m^3/s respectively). An increase in the stream power in the stream could result in a decrease in the areas of zero change. Also, for Forfar Creek, there appears to be a decreasing trend in the zero percent change with increasing gradient, excluding the 1997 Forfar 250 nival flood.

The 1996 summer flood average zero percent changes are shown in Table 9 and demonstrate a similar pattern as that of the nival floods. The average zero percent change is 11.8%, which is the same as the 1996 nival flood. This result is interesting since the summer flood peak streamflow was 7.26 m^3/s.

Table 10 shows the percentage results from the sockeye salmon spawning event. The zero percent changes due to the spawning events are generally higher than that flood related events. The spawning zero percent change varies from 13.4% in 1996 and 16.7%

in 1997. The trend in overall depth of disturbance appears to be more uniform between all stream sections while the flood related events show an increase in depth of impact with increasing stream gradient.

	Depth	Forfar 250		Forfar 1050		Fofar 1545		O'Ne-ell 925		O'Ne-ell 1550	
		1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
Cut Percentages	-0.80										0.1%
	-0.75										0.2%
	-0.70										0.3%
	-0.65										0.5%
	-0.60								0.0%	0.1%	0.6%
	-0.55								0.1%	0.4%	0.8%
	-0.50						0.1%		0.1%	0.7%	0.9%
	-0.45						0.4%		0.2%	1.2%	1.4%
	-0.40	0.0%					0.5%	0.1%	0.3%	1.8%	1.8%
	-0.35	0.1%					1.0%	0.6%	0.5%	2.6%	2.6%
	-0.30	0.2%				0.8%	1.9%	1.5%	0.8%	3.3%	3.3%
	-0.25	0.5%				1.9%	3.4%	2.4%	1.5%	4.1%	4.4%
	-0.20	1.4%			0.2%	4.0%	5.5%	4.6%	3.1%	5.5%	5.5%
	-0.15	3.7%	0.3%	0.2%	2.9%	6.1%	9.4%	7.9%	9.2%	7.7%	7.3%
	-0.10	12.1%	1.8%	2.7%	12.5%	8.7%	17.6%	19.8%	23.8%	10.3%	9.3%
	-0.05	29.3%	7.6%	12.4%	31.0%	13.2%	25.3%	32.6%	39.1%	15.5%	12.6%
± 1cm		19.9%	5.9%	13.5%	12.1%	8.8%	8.2%	10.3%	11.5%	6.9%	5.7%
Fill Percentages	0.05	28.0%	50.4%	36.7%	17.2%	24.8%	11.3%	10.0%	6.5%	14.8%	13.0%
	0.10	4.6%	27.6%	23.1%	10.5%	14.2%	7.2%	4.5%	2.4%	10.1%	9.1%
	0.15	0.4%	5.7%	9.2%	6.7%	7.5%	4.8%	2.0%	0.7%	6.9%	6.8%
	0.20		0.6%	2.2%	3.8%	4.3%	2.6%	1.2%	0.2%	4.0%	4.8%
	0.25		0.1%	0.1%	1.8%	2.5%	0.4%	0.9%	0.0%	2.3%	3.3%
	0.30				0.8%	1.1%	0.1%	0.7%		1.1%	2.2%
	0.35				0.4%	0.8%	0.1%	0.5%		0.4%	1.6%
	0.40					0.5%	0.1%	0.3%		0.1%	0.9%
	0.45					0.4%	0.0%	0.2%			0.5%
	0.50					0.2%	0.0%	0.0%			0.3%
	0.55					0.1%					0.1%
	0.60					0.0%					0.1%
	0.65										0.0%
	0.70										0.0%
	0.75										
	0.80										

Table 8: Nival Flood – Percent Volume Change in 5cm increments

	Depth	Forfar 250 1996	Forfar 1050 1996	Fofar 1545 1996	O'Ne-ell 925 1996	O'Ne-ell 1550 1996
Cut Percentages	-0.80					0.13%
	-0.75					0.26%
	-0.70					0.33%
	-0.65					0.47%
	-0.60			0.00%		0.54%
	-0.55			0.14%		0.71%
	-0.50			0.48%		0.82%
	-0.45			1.16%		1.04%
	-0.40			1.68%		1.38%
	-0.35			2.55%	0.09%	1.99%
	-0.30			3.30%	0.35%	2.55%
	-0.25	0.07%	0.06%	4.56%	0.88%	3.37%
	-0.20	0.57%	0.65%	5.56%	2.05%	4.01%
	-0.15	1.82%	1.16%	7.64%	5.87%	5.28%
	-0.10	4.91%	6.39%	9.89%	16.03%	7.29%
	-0.05	16.64%	19.48%	14.38%	33.69%	10.26%
± 1cm		14.85%	16.65%	6.01%	16.17%	5.33%
Fill Percentages	0.05	37.64%	36.58%	12.25%	18.91%	14.05%
	0.10	15.83%	14.06%	8.57%	4.36%	10.86%
	0.15	4.64%	4.32%	6.47%	1.07%	8.61%
	0.20	2.08%	0.65%	5.06%	0.42%	6.31%
	0.25	0.72%		4.01%	0.11%	4.67%
	0.30	0.22%		2.25%		3.29%
	0.35			1.41%		2.28%
	0.40			0.97%		1.21%
	0.45			0.79%		0.84%
	0.50			0.49%		0.64%
	0.55			0.29%		0.55%
	0.60			0.08%		0.37%
	0.65					0.26%
	0.70					0.15%
	0.75					0.10%
	0.80					0.03%

Table 9: Summer Flood – Percent Volume Change in 5cm increments

	Depth	Forfar 250		Forfar 1050		Fofar 1545		O'Ne-ell 925		O'Ne-ell 1550	
		1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
Cut Percentages	-0.80										
	-0.75										
	-0.70										
	-0.65										
	-0.60									0.00%	
	-0.55									0.02%	
	-0.50					0.02%				0.04%	
	-0.45					0.06%				0.10%	0.01%
	-0.40					0.09%				0.16%	0.09%
	-0.35					0.16%				0.29%	0.35%
	-0.30	0.15%	0.02%			0.22%		0.04%		0.75%	1.42%
	-0.25	0.86%	0.21%			0.44%		0.37%		1.72%	3.66%
	-0.20	2.32%	0.69%	0.67%		1.04%	0.00%	1.75%	0.26%	3.85%	6.13%
	-0.15	6.05%	3.27%	3.36%		3.26%	0.07%	5.27%	1.20%	8.16%	10.35%
	-0.10	17.89%	13.29%	11.01%	1.12%	9.85%	0.55%	13.21%	5.16%	16.75%	16.19%
	-0.05	34.37%	35.25%	28.79%	11.46%	19.81%	2.88%	28.88%	31.39%	27.79%	23.94%
± 1cm		18.72%	22.68%	16.51%	18.05%	9.45%	14.08%	12.87%	20.58%	9.31%	8.01%
Fill Percentages	0.05	11.88%	16.05%	25.50%	44.73%	20.90%	50.84%	16.67%	27.63%	12.46%	11.52%
	0.10	5.11%	5.61%	9.26%	19.27%	14.47%	20.58%	8.65%	8.64%	7.18%	7.17%
	0.15	2.07%	1.88%	3.62%	4.46%	9.13%	8.05%	5.40%	3.44%	3.86%	4.63%
	0.20	0.54%	0.84%	1.21%	0.91%	5.44%	2.38%	3.58%	1.43%	2.20%	2.87%
	0.25	0.04%	0.21%	0.07%		3.50%	0.45%	2.05%	0.24%	1.45%	1.55%
	0.30					1.56%	0.12%	1.02%	0.02%	0.92%	0.93%
	0.35					0.49%		0.24%		0.72%	0.59%
	0.40					0.10%		0.00%		0.56%	0.33%
	0.45									0.48%	0.21%
	0.50									0.36%	0.05%
	0.55									0.30%	
	0.60									0.21%	
	0.65									0.16%	
	0.70									0.10%	
	0.75									0.08%	
	0.80									0.03%	

Table 10: Redd Excavation – Percent Volume Change in 5cm increments

Tables 8,9,10 were presented to demonstrate the dispersion in the volume change in 5 cm increments. A summary of Tables 8,9,10 is presented in Table 11. The total volume change percentages were added for the cuts (erosional area) and the fills (depositional area) and are described as "Total Fill" and "Total Cuts". The zero (±1 cm) volume change areas have been treated separately to demonstrate the areas of zero change. It is interesting to note that the average for total cuts and total fill tend to be nearly balanced. The nival and summer flood zero volume change values are similar with 10% and 12%. The redd excavation zero volume change is slightly higher with a reported value of 15%.

	Forfar 250		**Forfar 1050**		**Fofar 1545**		**O'Ne-ell 925**		**O'Ne-ell 1550**		Average
Stream Gradient	0.50%		0.90%		1.70%		0.55%		0.50%		
Study Year	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	
Nival flood											
Total Fill	33%	84%	71%	41%	57%	27%	20%	10%	40%	43%	43%
Zero Change	**20%**	**6%**	**13%**	**12%**	**9%**	**8%**	**10%**	**12%**	**7%**	**6%**	**10%**
Total Cut	47%	10%	15%	47%	35%	65%	69%	79%	53%	52%	47%
Summer Flood											
Total Fill	61%		56%		43%		25%		54%		48%
Zero Change	**15%**		**17%**		**6%**		**16%**		**5%**		**12%**
Total Cut	24%		28%		51%		59%		40%		41%
Redd Excavation											
Total Fill	20%	25%	40%	69%	56%	82%	38%	41%	31%	30%	43%
Zero Change	**19%**	**23%**	**17%**	**18%**	**9%**	**14%**	**13%**	**21%**	**9%**	**8%**	**15%**
Total Cut	62%	53%	44%	13%	35%	4%	50%	38%	60%	62%	42%

Table 11: Summary of Percentage of Volume Change for Total Fills, Total Cuts and Zero Change for all Events

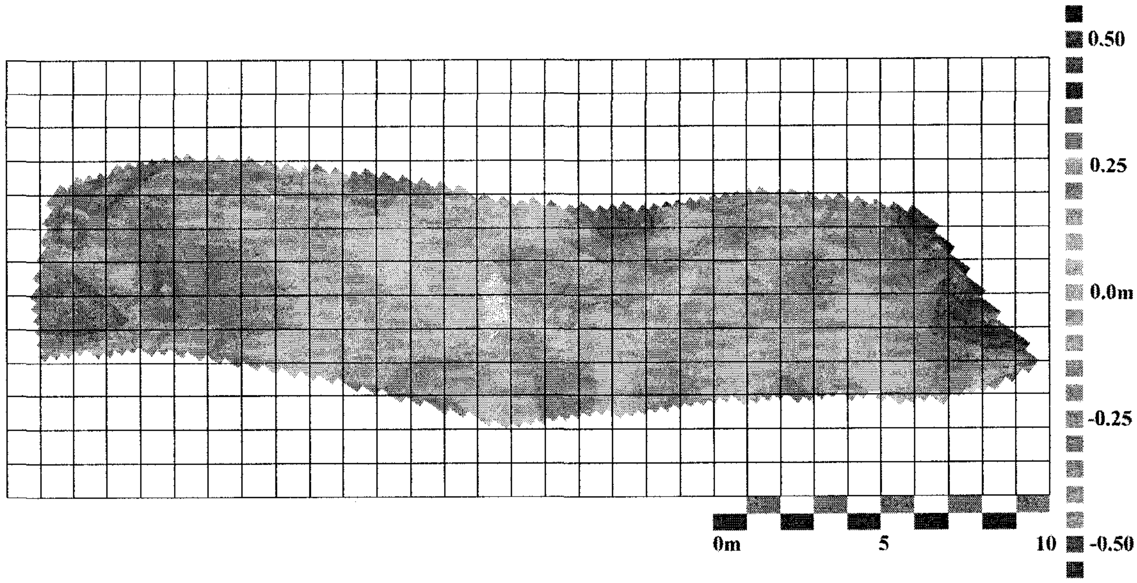

Figure 50: Forfar 250 1996 Nival Flood Isopach Map

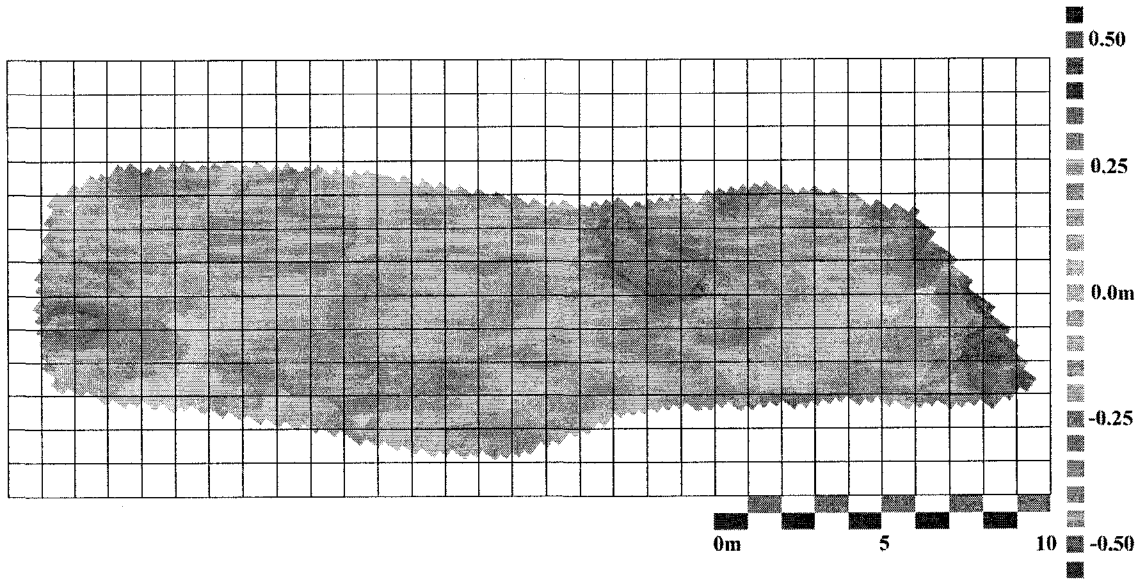

Figure 51: Forfar 250 1996 Summer Flood Isopach Map

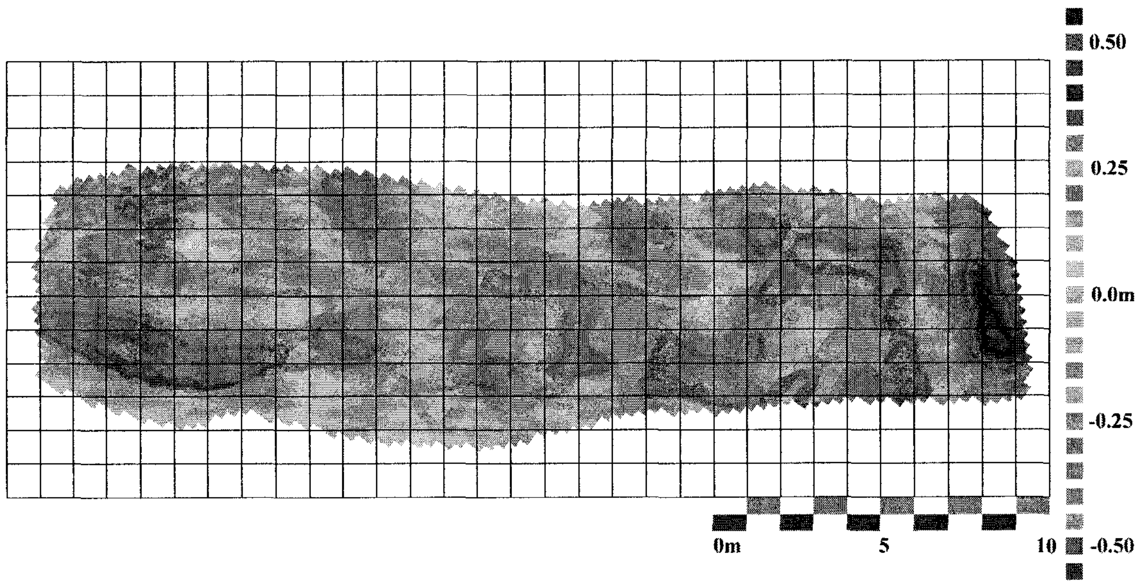

Figure 52: Forfar 250 1996 Spawning Event Isopach Map

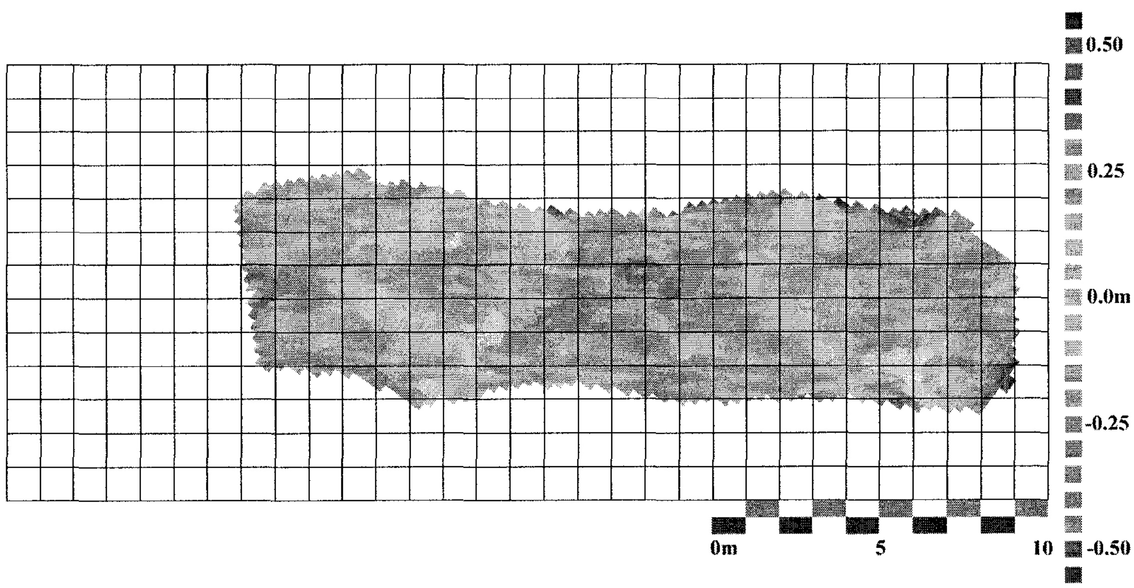

Figure 53: Forfar 250 1997 Nival Flood Isopach Map

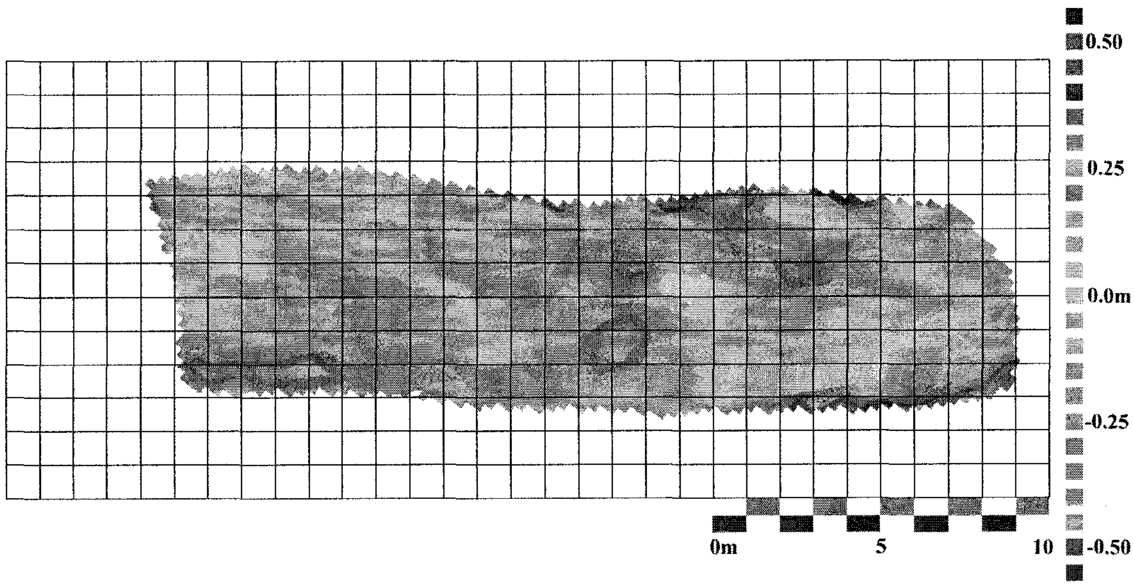

Figure 54: Forfar 250 1997 Spawning Event Isopach Map

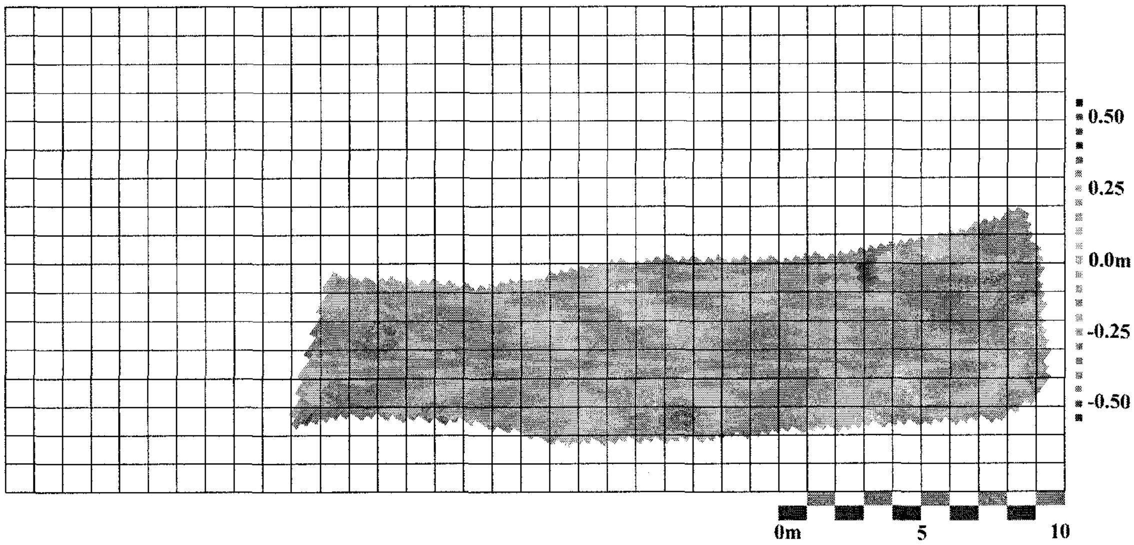

Figure 55: Forfar 1050 1996 Nival Flood Isopach Map

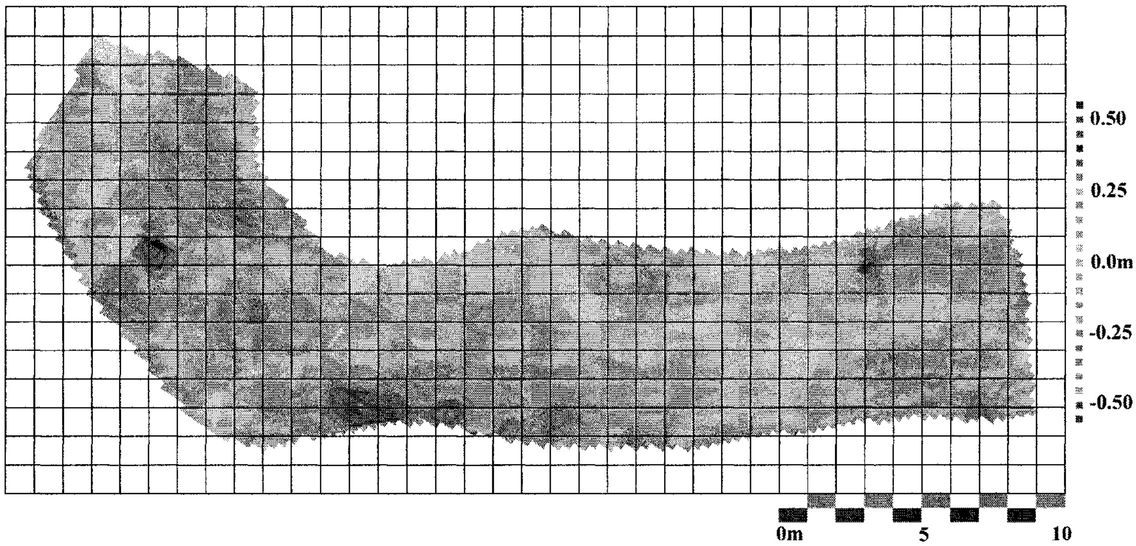

Figure 56: Forfar 1050 1996 Summer Flood Isopach Map

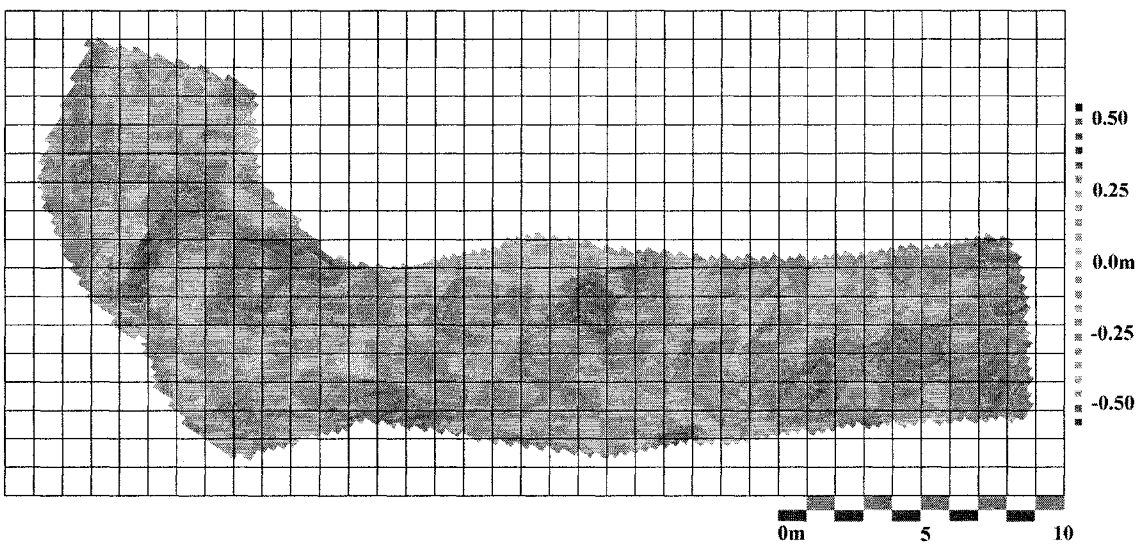

Figure 57: Forfar 1050 1996 Spawning Event Isopach Map

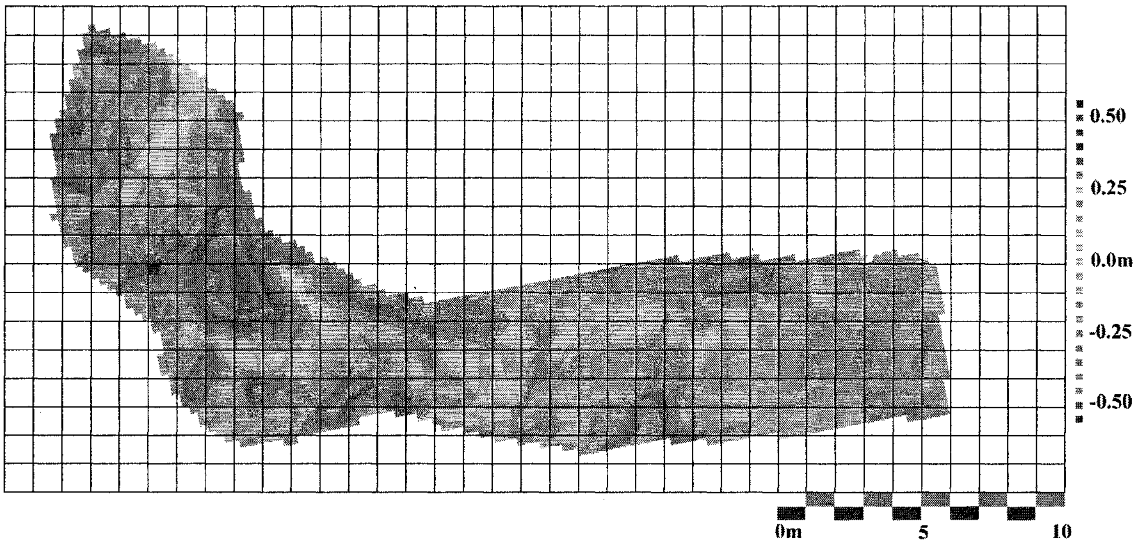

Figure 58: Forfar 1050 1997 Nival Flood Isopach Map

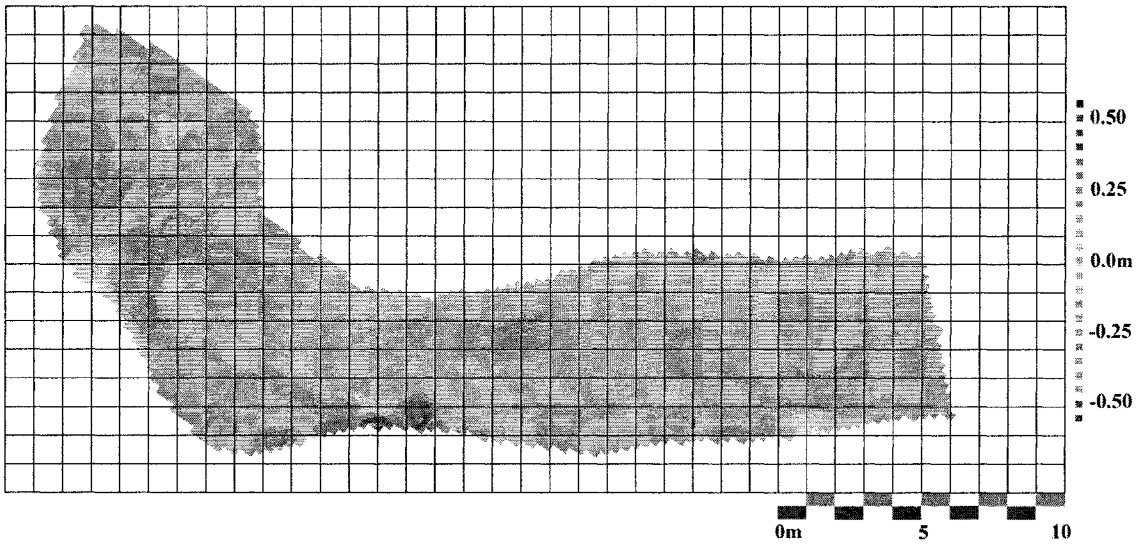

Figure 59: Forfar 1050 1997 Spawning Event Isopach Map

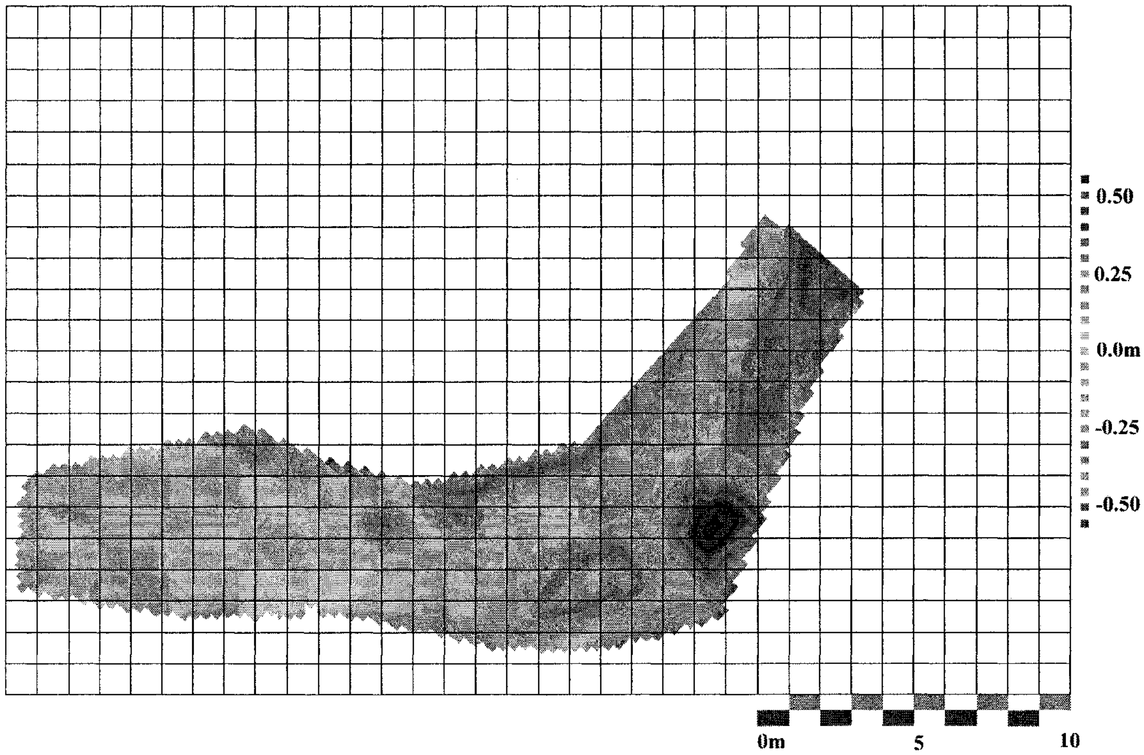

Figure 60: Forfar 1545 1996 Nival Flood Isopach Map

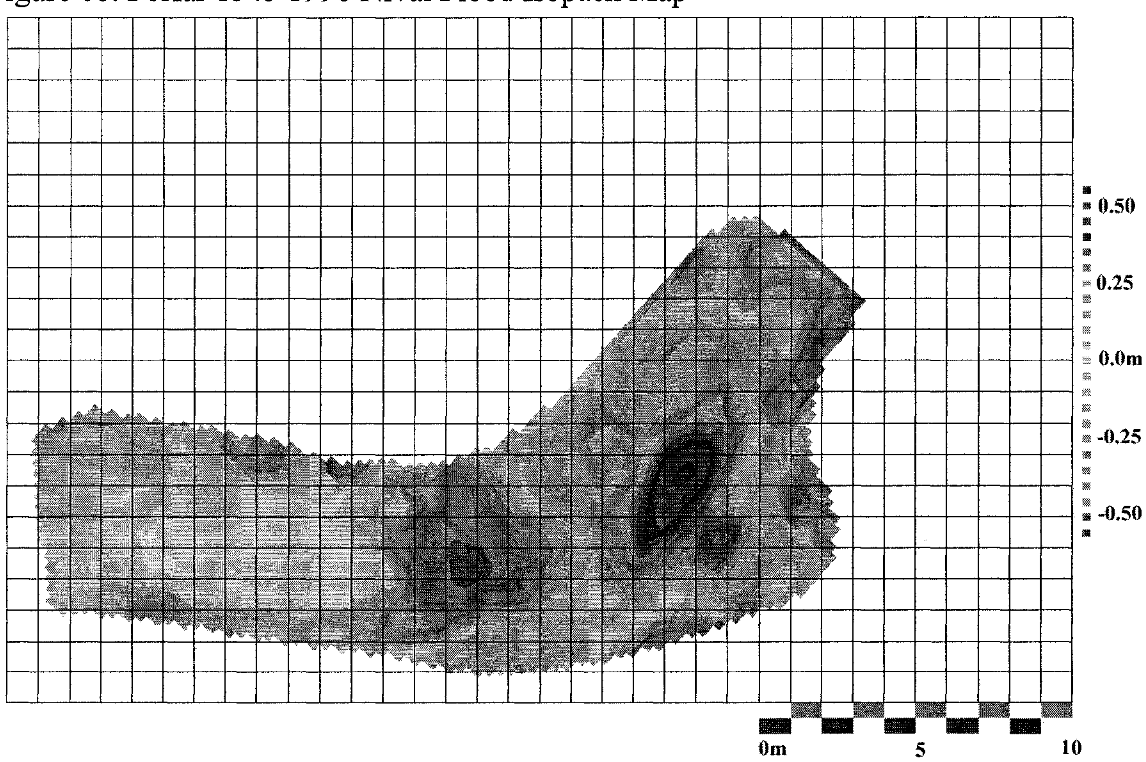

Figure 61: Forfar 1545 1996 Summer Flood Isopach Map

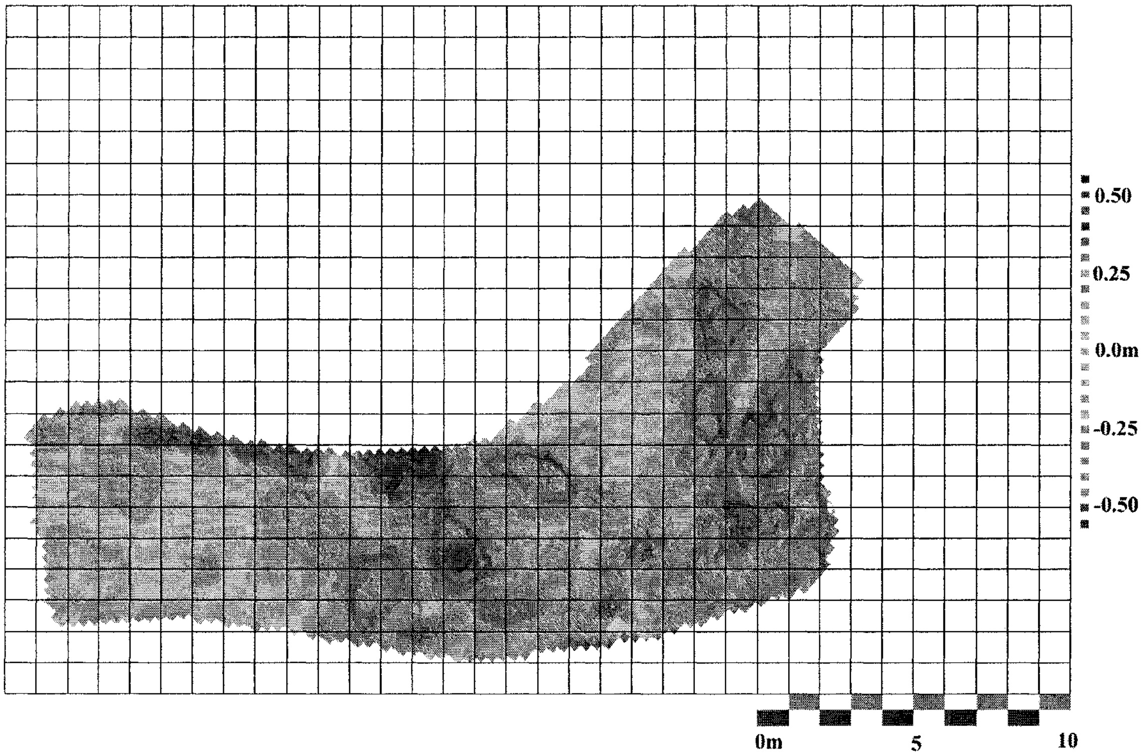

Figure 62: Forfar 1545 1996 Spawning Event Isopach Map

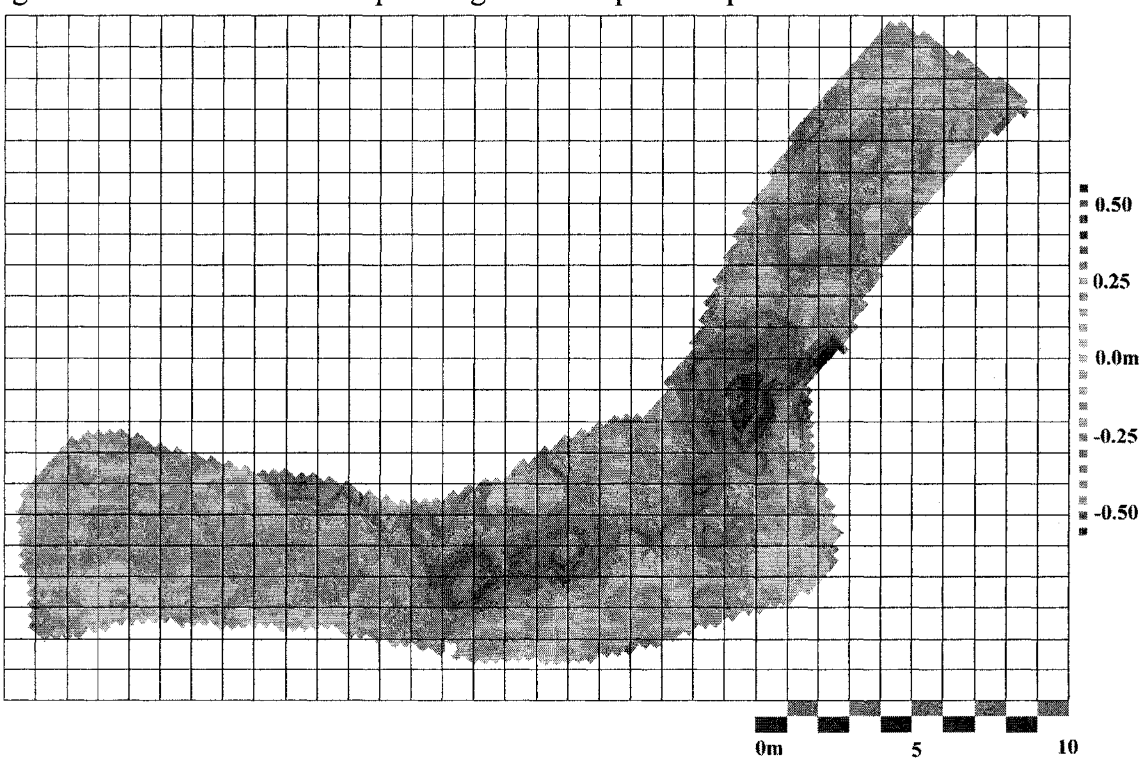

Figure 63: Forfar 1545 1997 Nival Flood Isopach Map

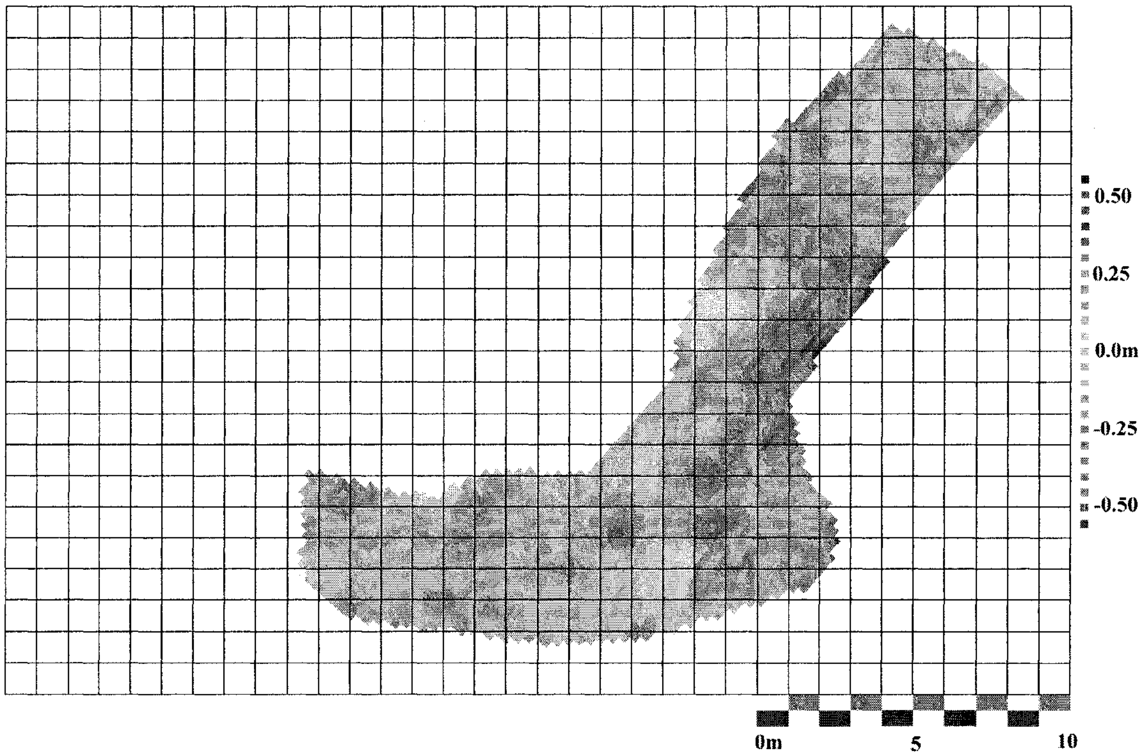

Figure 64: Forfar 1545 1997 Spawning Event Isopach Map

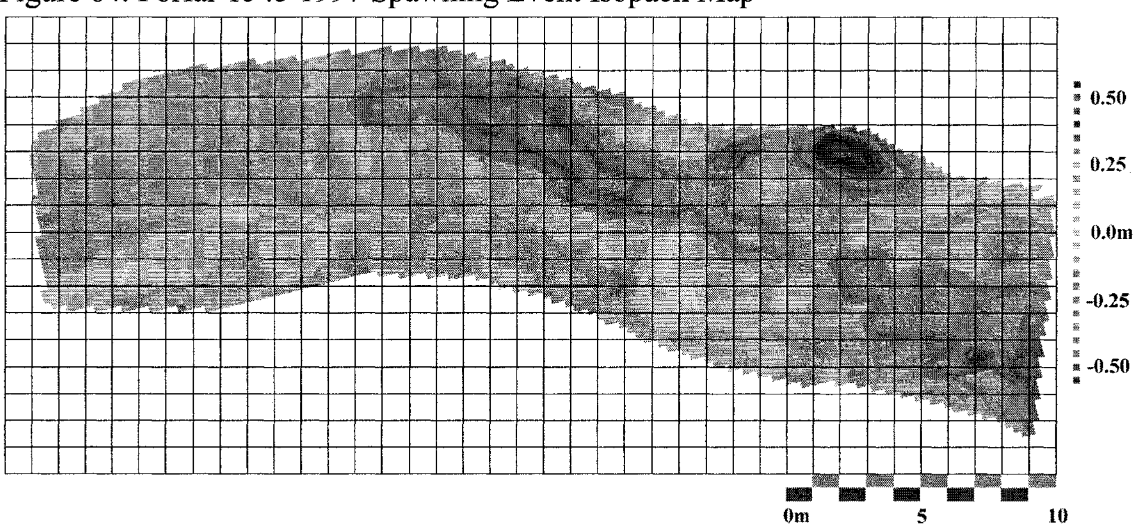

Figure 65: O'Ne-ell 925 1996 Nival Flood Isopach Map

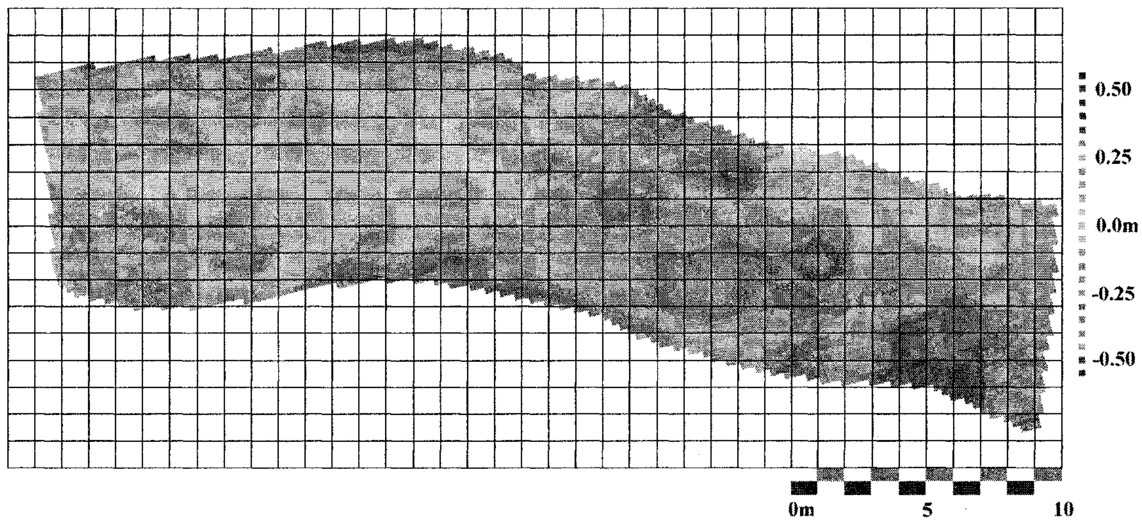

Figure 66: O'Ne-ell 925 1996 Summer Flood Isopach Map

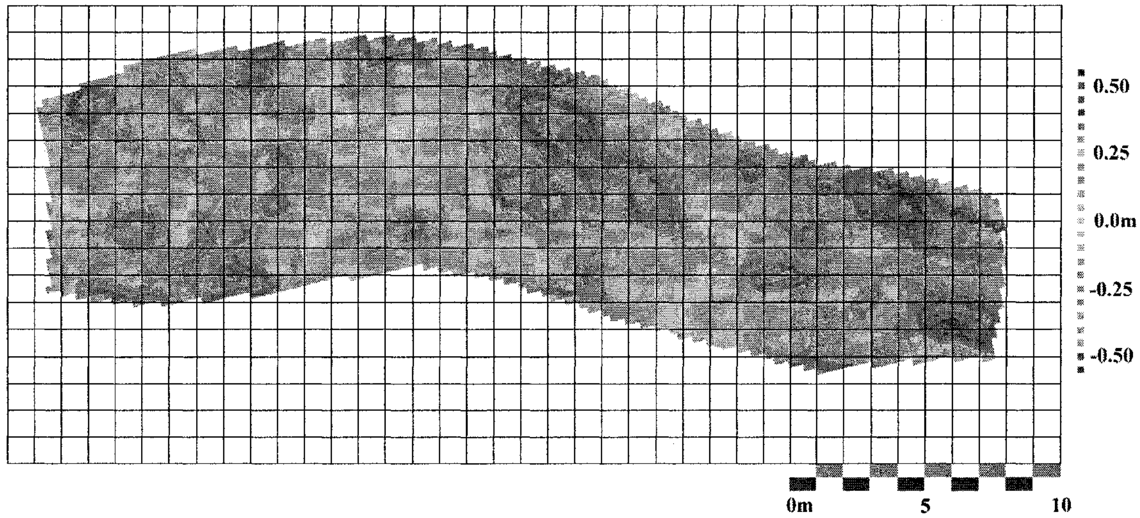

Figure 67: O'Ne-ell 925 1996 Spawning Event Isopach Map

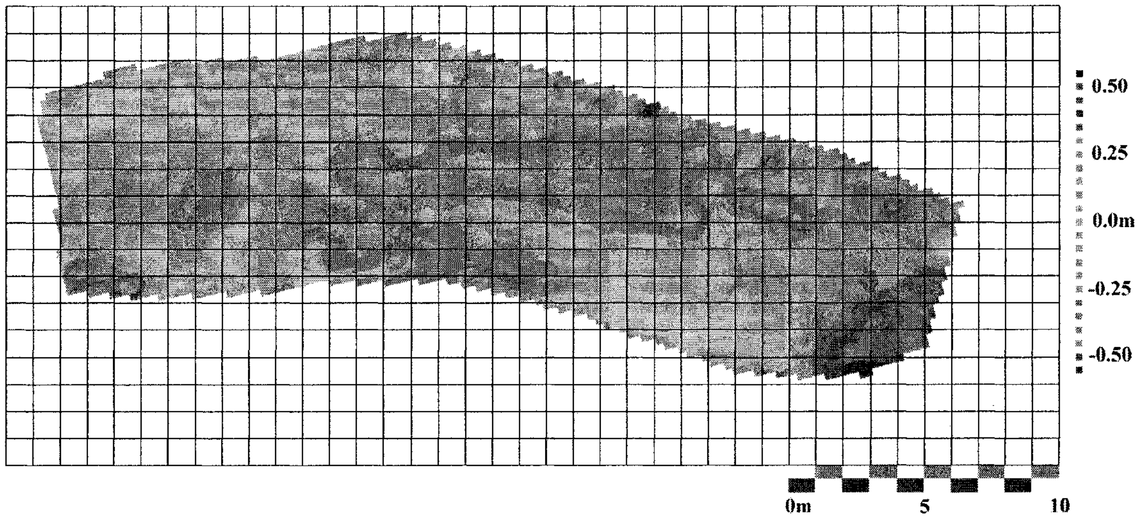

Figure 68: O'Ne-ell 925 1997 Nival Flood Isopach Map

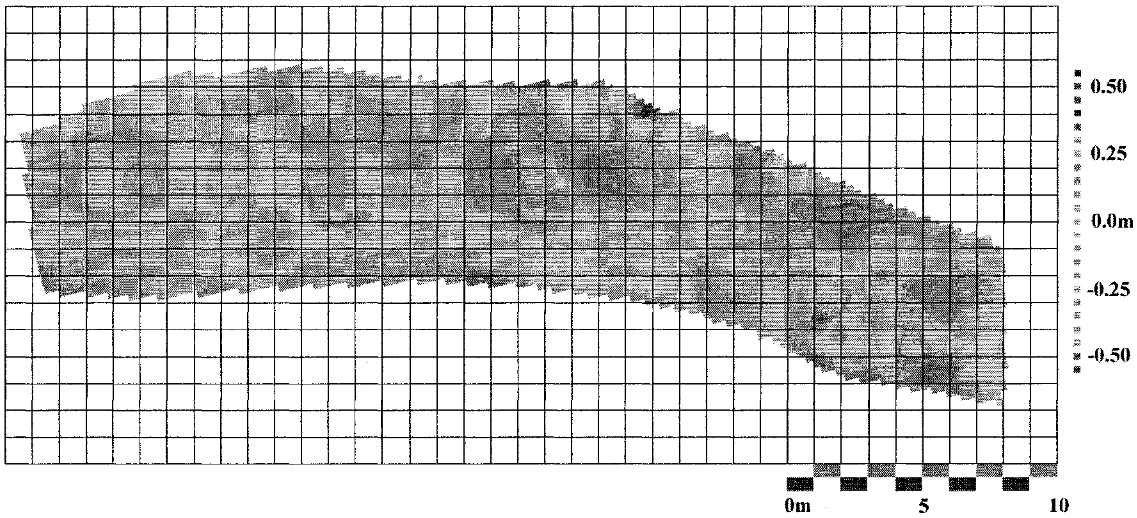

Figure 69: O'Ne-ell 925 1997 Spawning Event Isopach Map

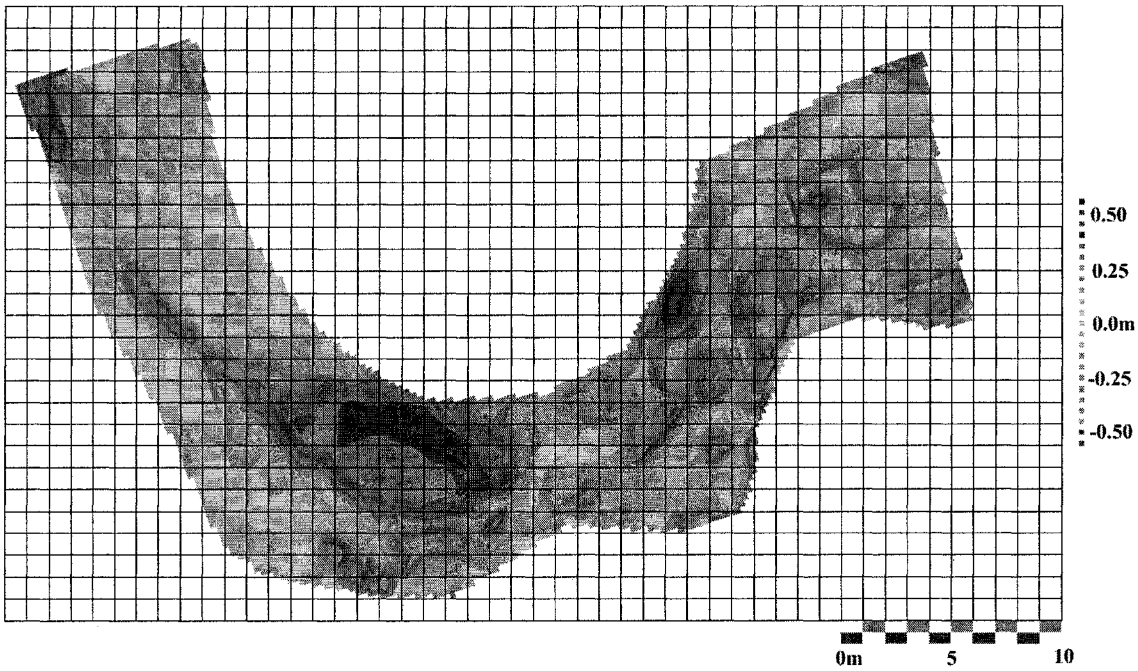

Figure 70: O'Ne-ell 1550 1996 Nival Flood Isopach Map

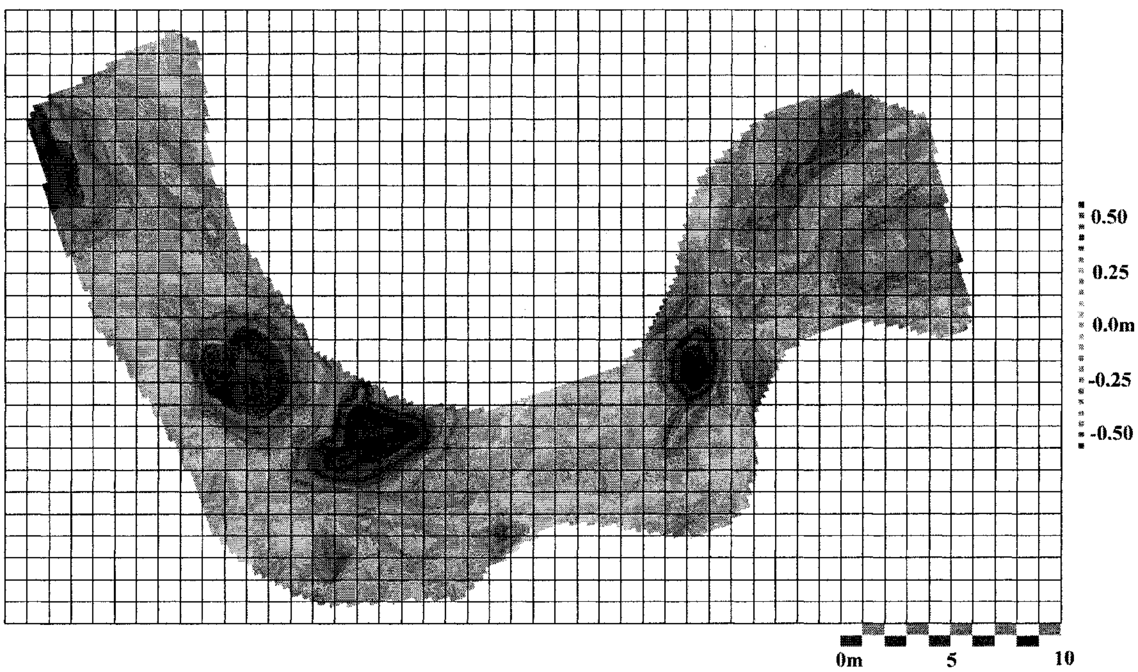

Figure 71: O'Ne-ell 1550 1996 Summer Flood Isopach Map

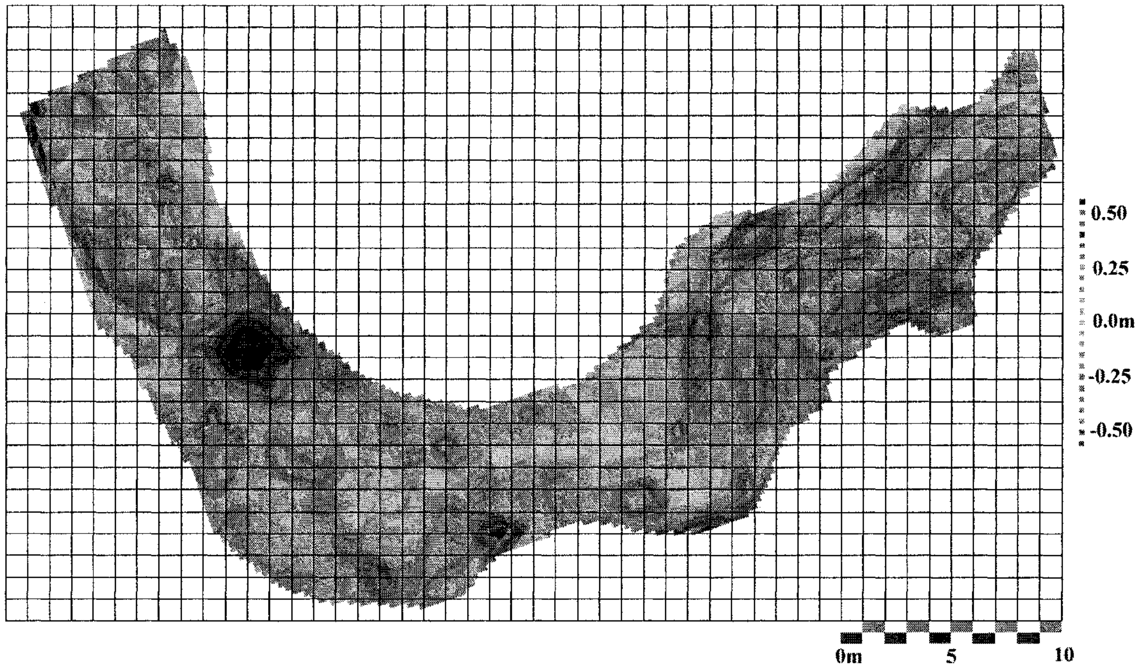

Figure 72: O'Ne-ell 1550 1996 Spawning Event Isopach Map

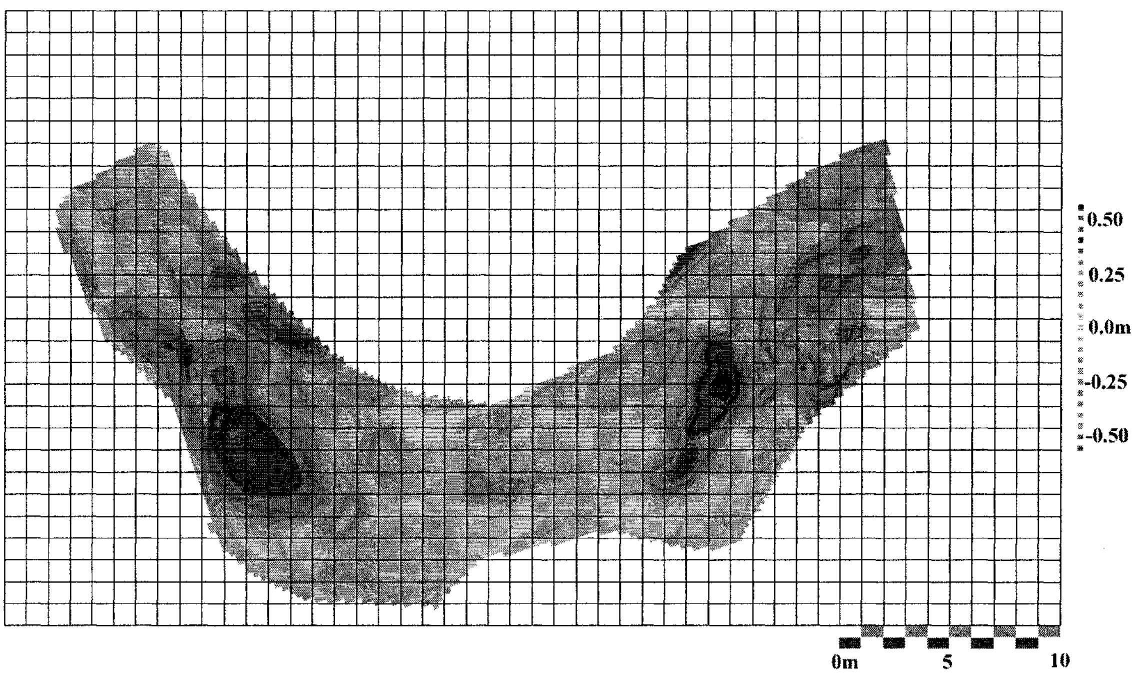

Figure 73: O'Ne-ell 1550 1997 Nival Flood Isopach Map

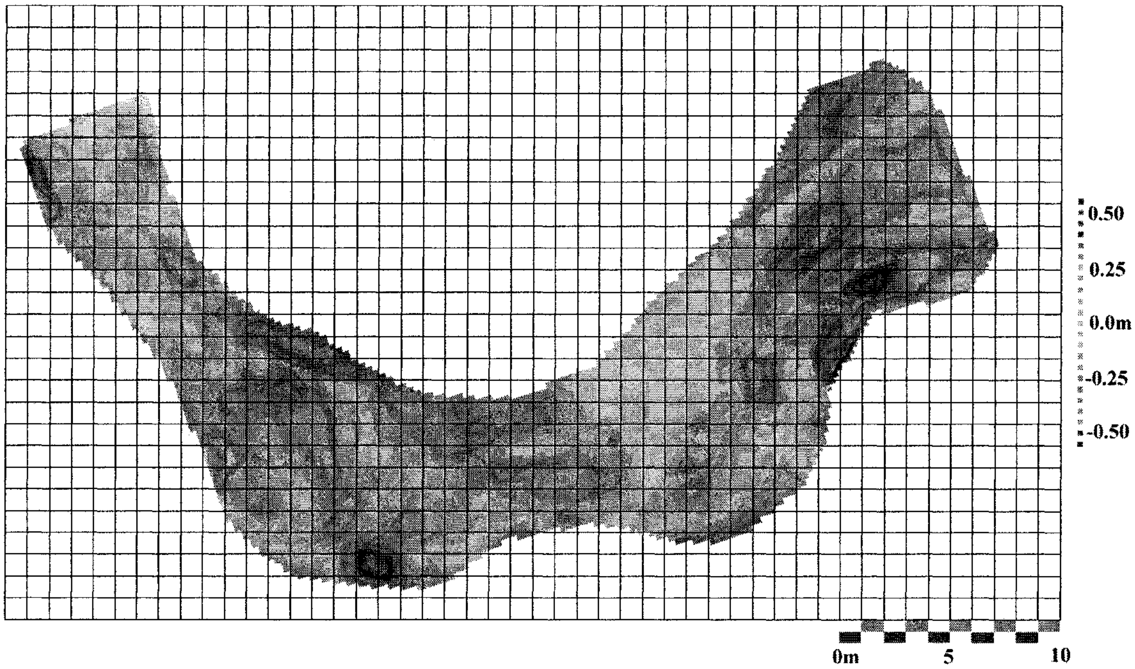

Figure 74: O'Ne-ell 1550 1997 Spawning Event Isopach Map

Chapter Five

Discussion

5.0 Introduction

This section will discuss the results of my research in six main sections: process relationships between the flood events and the sockeye salmon bioturbation events, flood transport, redd excavation transport, a discussion of the pattern of changes of the streambed, a discussion of the roughness index, and the effective depth of change.

5.1 Process relationships

By the time the redd excavation is under way in these streams, nival and summer floods had altered their morphology, from hummocky to linear. These floods produced freshly deposited, surface gravels, which had a loosely compacted surface and therefore could easily be altered during the spawning process.

The sockeye salmon redd excavation event and the nival and summer flood events are not related processes other than the fact that they occur in the same stream, and that the same stream substrate is involved. But as the two processes alternate each year we can see that in some ways they complement each other.

One should note that the sockeye spawning events tend to occur during the period of low stream flows, in the late summer. Even in 1996 the stream flows preceding the post summer flood survey, had substantially receded. At the end of the post summer flood survey on July 18,1996 the first sockeye salmon were observed at O'Ne-ell 925.

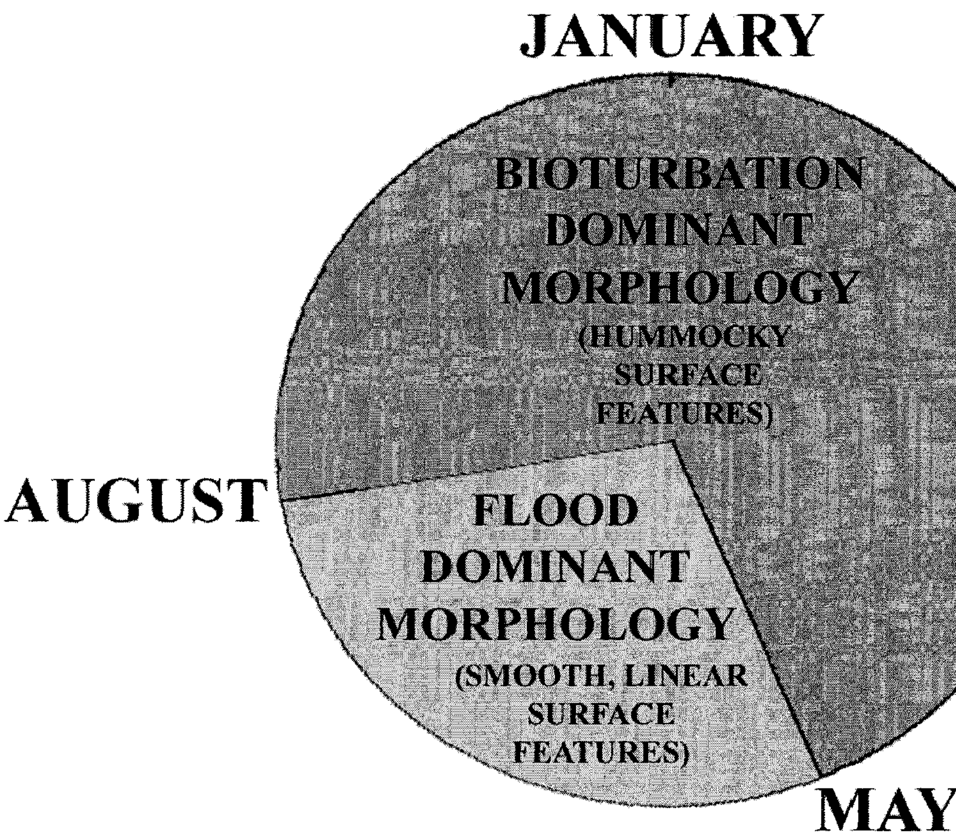

Figure 75: The Annual Cycle of Streambed Reorganization

Figure 75 is a diagrammatic representation of the effects of bioturbation and hydrological events on a yearly cycle. Nival floods tend to occur in May or June while the spawning event occurs at the end of July or August. From the nival event up until the sockeye salmon spawn, the streambed surface morphology reflects the flood surface features. The streambed surface features are smooth and linear. Following the sockeye salmon spawning event, the streambed surface morphology is hummocky. This surface morphology is retained until the following major flood event, which is typically the following year, associated with the spring snowmelt. This hummocky morphological pattern has been observed in many of the streams section under study. The implication of this observation is that in these streams, the sockeye salmon redd excavation event dominates the streambed surface morphology most of the year.

The primary objective of this research thesis was to compare the volumes of change resulting from flood events and bioturbation for five stream sections. From Table 6, the average unit bed load volume for nival and summer flood events is calculated as 0.045m ± .015 and the average unit bed load volume for spawning events is 0.034m ± .012. This is a very similar level of impact for very different processes. A t-test shows that two means are not statistically different at the 95% confidence limit.

Nival and summer flood unit bed load volumes are positively correlated with stream gradient for Forfar Creek sites. The stream gradient was plotted against the average depth of change for both the flood and bioturbation events (Figure 76). Floods events demonstrate a positive relationship between stream gradient and average depth of change, with an R^2 of 0.65. The same relationship for bioturbation events resulted in an R^2 of 0.0055 demonstrating a lack of correlation with stream gradient. Since there were only two stream sections studied and the stream gradients were similar for both stream sections on O'Ne-ell Creek, a similar analysis could not be attempted.

The highest depth of change is at the O'Ne-ell 1550 stream section in both the redd excavation and flood events. O'Ne-ell 1550 stream section has been observed to be a depositional zone, with a vast quantity of material eroded and transported in floods, creating an area of loose bed material allowing for easy nest excavation. This could explain the high depth of change measured from the spawning activity.

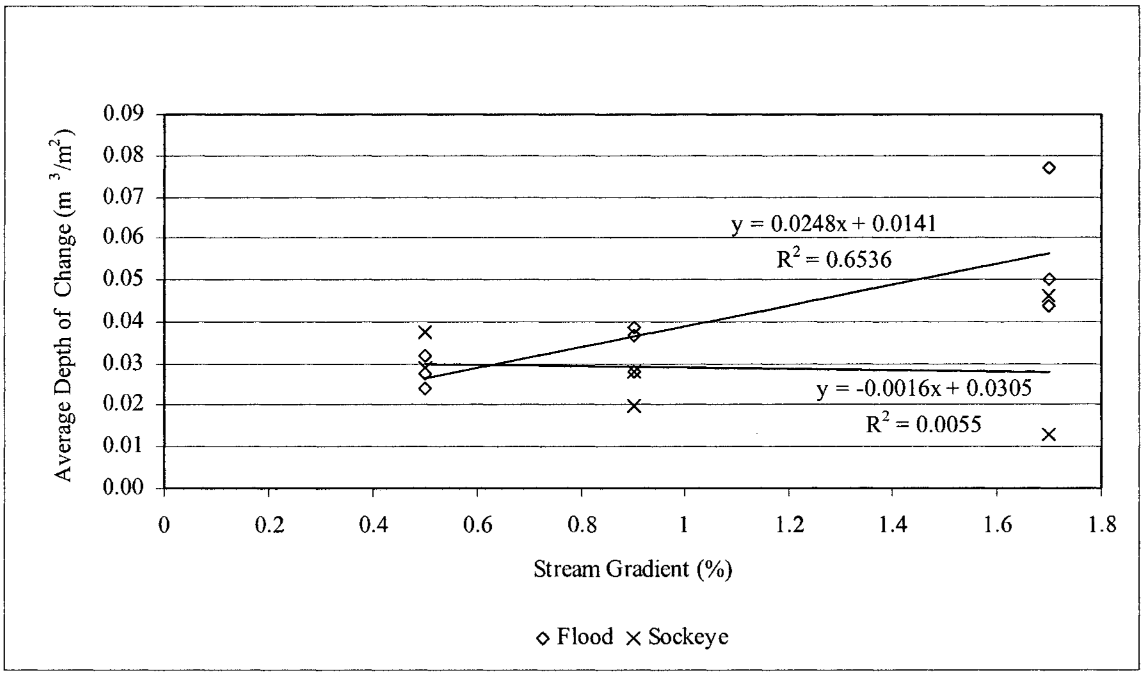

Figure 76: Stream Gradient against Average Depth of Change for Forfar Creek

5.2 Flood Transport

To compare the flood processes to the redd excavation processes; the concept of stream power is used as it is the only common variable between both events. The stream power was calculated over the period of each event. This was achieved using the streamflow hydrograph over the period between each survey. The average stream power was calculated by summing the daily stream power for each survey period and then dividing by the number of days between each survey (Table 12).

	Forfar Creek					
	250 s = 0.50%		1050 S = 0.90%		1545 s = 1.70%	
Event (Duration (Days))	**Stream Power kg m s^{-2}**	**Depth of Change m**	**Stream Power kg m s^{-2}**	**Depth of Change m**	**Stream Power kg m s^{-2}**	**Depth of Change m**
1996 Nival Flood (63)	1238.12	0.024	2228.62	0.037	4209.62	0.044
1996 Summer Flood (20)	1286.19	0.032	2315.14	0.028	4373.05	0.077
1997 - Nival Flood (73)	471.47	0.028	848.66	0.039	1603.05	0.050
1996 - Spawning Period (24)	1538.21	0.038	2418.85	0.028	4569.01	0.046
1997 - Spawning Period (60)	270.02	0.029	454.80	0.020	859.06	0.013

	O'Ne-ell Creek			
	925 s = 0.55%		1550 S = 0.50%	
Event	**Stream Power kg m s^{-2}**	**Depth of Change m**	**Stream Power kg m s^{-2}**	**Depth of Change m**
1996 Nival Flood (63)	3116.52	0.047	2833.20	0.062
1996 Summer Flood (20)	2761.82	0.028	2510.75	0.063
1997 - Nival Flood (73)	828.55	0.043	1235.28	0.077
1996 - Spawning Period (24)	3202.47	0.037	4774.53	0.060
1997 - Spawning Period (60)	361.96	0.022	329.06	0.050

Table 12: Total Stream Power and Average Depth of Change for each Sample Reach

Figure 77 is a graph of the average stream power versus the average depth of change using Table 11. Both the redd construction and the flood "average depth of change" demonstrate a positive relationship between stream power and average depth of change.

The regression lines fitted for the salmon and hydrologic events exhibit coefficients of determination (R^2) of 0.24 and 0.73 respectively.

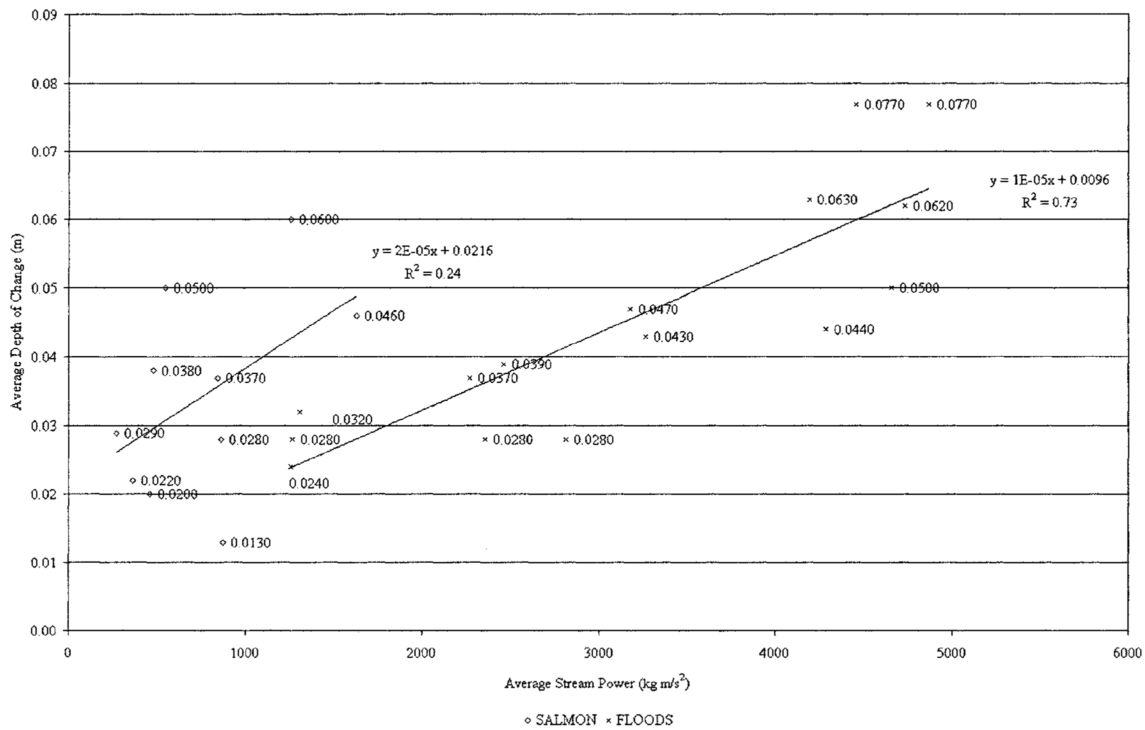

Figure 77: Average Stream Power Versus Average Depth of Change for Floods and Spawning Events

Graphically, the two processes separate into distinct groups, showing the independent nature of the events. This is an expected result as the sockeye salmon generally spawn during a period of low stream discharge, when water velocities are too low to substantially transport gravel. During redd excavation distance of travel of the ejected rocks have a dependence on the force from the fish and then the stream flows. Once the static coefficient of friction has been overcome by the fish which excavates and ejects it, the dynamic coefficient of friction applies to the moving particle, which is then a function of the stream velocity. In a comparative study of rock travel distances in these same streams, Gottesfeld (1998) reported that spawning fish moved the tracer rocks an average of 2.2 m while the spring floods were associated with average distances of 11.2 m.

The depths of change for redd excavation events compare well with flood events for low to medium stream power. The higher stream power data points reflect the higher stream gradient sections where flood events demonstrate greater depths of change than observed in any redd excavation events. This result demonstrates the nature of the process. As the stream gradient increases within a stream section the potential energy increases resulting in higher stream velocities. Higher stream velocities imply higher shear stress resulting in movement of larger and potentially more material. The effect of sockeye salmon spawning over the streambed is independent of the stream gradient. Rather the depth of the excavated redd is dependent on the digging behavior of the salmon and the size of the substrate.

5.3 Spawning Transport

The previous section shows that stream power poorly predicts depth of change associated with redd excavation , therefore, a comparison of the number of female sockeye salmon to volume of change will be explored. Early during the spawning period, dominant females select the choicest areas. As the density of fish increases in the stream, the fish start digging in less preferable areas or move further upstream to find suitable spawning areas. After the spent salmon die, the constructed redd is left unguarded and the site may be used by another female arriving later. As the spawning population increases, the likelihood increases that a second female digs another redd in the same location. This process is termed reworking the gravels. It is likely that the volume of material moved by redd excavation is linked to the total number of female sockeye salmon who do the work to excavate the redds.

Data provided by the Department of Fisheries and Oceans (DFO) provides total adult escapement counts separated by gender (Table 13). The 1996 male to female ratio is approximately 1:1, for both creeks whereas in 1997 the male to female ratio was approximately 2:1, for both creeks.

Forfar Creek

Year	Male	Female	Total
1996	4452	4586	9038
1997	9226	4571	13797

O'Ne-ell Creek

Year	Male	Female	Total
1996	5642	5653	11295
1997	13546	7599	21145

Table 13: Stock Assessment Count

The weakness of the DFO data is that they do not define to how many of the salmon utilized each specific stream section. Unpublished data provided by Peter Tschaplinski, of the B.C. Ministry of Forests Research Branch, enabled this estimate of the female sockeye salmon spawning count in the five stream sections under study as he collected temporal and spatial salmon distribution for Forfar and O'Ne-ell Creeks during the entire spawning period. The total number of sockeye salmon were counted every couple of days and categorized by 30 m reach distances (strip counts) from the mouth going upstream.

Using this strip count information, a density per linear meter was calculated by summing up the entire series of strip counts. As the 30 m reach divisions did not exactly match the stream sections surveyed for this project, the strip count data was summed for the appropriate areas and divided by the strip count spacing length. The result is termed "salmon per linear meter" and is reported in Table 14. By combining the female to male ratio with the salmon per linear meter and the length of my stream survey, an estimate of the total female sockeye salmon contained in the stream reached was obtained (Table 14).

Stream	Spawning Year	Stream Length (m)	Male to Female Ratio	Salmon per Linear Metre	Calculated Salmon for Stream Study Section	Average Depth of Change (m)
Forfar 250	1996	23	0.51	17.8	207.3	0.0380
Forfar 250	1997	23	0.33	55.3	421.1	0.0290
Forfar 1050	1996	42	0.51	14.1	300.7	0.0280
Forfar 1050	1997	42	0.33	11.2	156.0	0.0200
Forfar 1545	1996	47	0.51	12.1	288.8	0.0460
Forfar 1545	1997	47	0.33	4.0	62.5	0.0130
O'Ne-ell 925	1996	37	0.50	15.0	278.2	0.0370
O'Ne-ell 925	1997	37	0.36	22.3	296.2	0.0220
O'Ne-ell 1550	1996	68	0.50	15.3	519.6	0.0600
O'Ne-ell 1550	1997	68	0.36	12.4	302.5	0.0500

Table 14: Total Female Sockeye Salmon per Stream Section

The calculated total number of salmon for each stream study section was the graphed against the average depth of change (Figure 78).

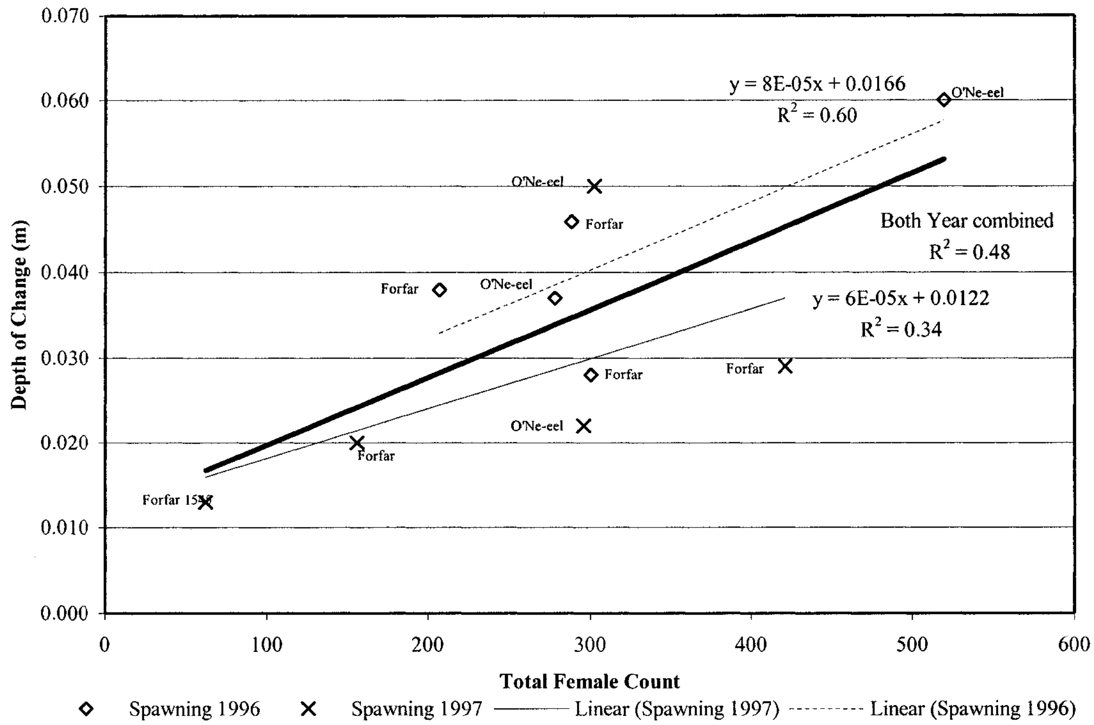

Figure 78: Sockeye Female Count Versus Depth of Change

The 1996 spawning activity displays a positive relationship between average depth of change and the total female count in the streams. The coefficient of determination for the 1996 spawning activities is 0.60. This is significant at $p < 0.05$. The 1997 spawning activity has a much lower and statistically insignificant at $p < 0.05$ with coefficient of determination of 0.37. This is attributed to O'Ne-ell Creek, which has a high depth of change with a low total female count return. It is possible that the enumerations underestimate the number of female sockeye salmon in these streams. Assuming that the 1997 O'Ne-ell Creek was totally in error, a regression analysis of the four remaining sample points reported a coefficient of determination of 0.76. Another possible explanation for this variable result is that the 1997 female numbers represent the total number of female sockeye salmon to alter the streambed and while the 1996 females are in high enough densities that the same gravels are simply reworked by the rest of the female sockeye salmon.

5.4 Patterns of morphological changes

The patterns of morphological change are important in understanding the effects of each process on the streambed. For example, the formation of a hummocky topography on the streambed likely increases turbulent flow over the spawning areas. Stuart 1953 demonstrated the presence of downwelling currents in the transitional areas at the downstream ends of redds. Water flows out of the gravels at the upstream end of the redds and into the gravels at the downstream end of the redds. Thus there is an increase in the overall hyporheic flow (Figure 79). This current increase within the inter-gravel flow brings fresh oxygen to the deposited eggs and removes the metabolic waste from the nest area increasing the survival rate of the eggs (Bjorn and Reiser 1991, Montgomery et al. 1996).

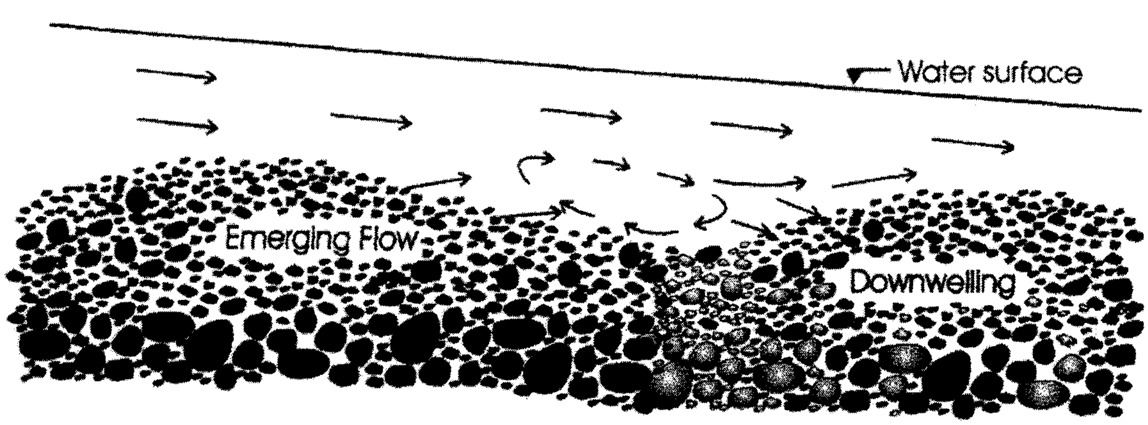

Figure 79: Downwelling Resulting From Turbulent Flow

The distance between fill areas on the isopach maps suggest that the transport distance is greater for the flood events than the spawning events. The flood events tend to have longer elongated features while the spawning events tend to have shorter oblong surface features. These results correlate well with Gottesfeld's study (1998) of transport distance of nival flood and spawning events. During flood conditions, the bed load is transported through the pool to rest on the next downstream gravel bar. The bed load can remain there or be transported one more steplength, through the next pool and to the next downstream gravel bar. During the spawning event, the gravel is dislodged and tends to move short distances downstream. The pools, being the lowest areas in the stream, tend to collect the disturbed bed load. The pools at low to mid flow conditions have lower velocities than the riffles and the collected gravels remains there until the stream discharge increases enough for current induced bed load movement to occur.

The flood events tend to deepen the pools, and the transported material results in an aggradation of downstream bars and point bars. The resulting streambed surface tends to be smooth and linear. The spawning events act in opposing fashion by excavating the sides of the point bars and the riffles with the excavated material moving downstream into nearby pools and the thalweg. The resulting streambed surface tends to be undulating and hummocky. The redd excavation process tends to fill in the pools and create hummocky features on the riffles. Floods following the redd excavation event, reestablish a purely fluvial stream pattern, re-excavating the thalweg and linearizing the riffle.

The alternating pattern of these two separate processes probably increases the mobility of streambed. The freshly deposited gravels from the flood event are remobilized by the action of the redd construction of the salmon, thus increasing the total volume of material in transit.

Once the stream has reestablished its flood morphology, the excess stream power can then erode the stream banks. Although there is no conclusive evidence, the spawning event might act as a stabilizing feature in that there is less channel morphological change, since following the spawning event, the nival event must reestablish the flood streambed conditions prior to further stream meandering.

5.5 Roughness Index

The roughness index is defined here as the ratio of the surface area to the plan area of the study reach and is expressed as a percentage greater than 100%. As the surface becomes rougher, the ratio of surface to plan area increases. This roughness measurement includes both the roughness from channel scale features and the roughness from the hummocky redd hollows and tail spills. Roughness indices were calculated for all reaches for both flood events and redd excavation and are reported in Table 15.

TIME OF SURVEY		Forfar Creek			O'Ne-ell Creek	
		250	1050	1545	925	1550
1996	Post Nival Flood	1.38	1.99	2.55	1.69	2.79
	Post Summer Flood	1.33	1.78	3.31	1.56	3.11
	Post Spawning Event	2.32	2.04	3.80	2.10	3.73
1997	Post Nival Flood	2.48	1.91	3.01	1.85	3.12
	Post Spawning Event	1.63	2.12	3.02	1.57	3.08

Table 15: Roughness Index for Each Reach and Event

In general, the redd excavation roughness values are greater than the flood events but there is much overlap. In all cases the 1996 redd excavation roughness indices are higher than the 1996 nival and summer flood values. The 1997 redd excavation roughness indices are all lower than the spawning event values for 1996 and in three of the five stream reaches they are lower than the roughness index for the nival flood. This pattern might be an indication of the success of the redd excavation process in 1996, while the low roughness values could be the result of the poor condition of spawning females due to the 1997 Fraser River high waters.

As a second metric of the gravelbed surface variability, the standard deviation of the streambed elevation survey was obtained from the survey data. The deep scours of the pools as well as the deposition generating high gravel bar disproportionately influences the calculated standard deviation. This means that the standard deviation can be strongly influenced by the larger scale roughness of the channel. In making this calculation to characterize the streambed, the stream bank elevations were not included, as they would strongly bias the results.

When the roughness index, is plotted against the standard deviation of elevation, (Figure 80), it appears that the effects of redd excavation on the streambed separate from the effects of floods such that they fall into two separate fields. To demonstrate this, a line was fitted to separate the processes. Note that some overlap of fields occurs when there is a large flood or when the spawning success is low. Also, the graph shows that floods produce relatively large scale features and redd excavation produces relatively smaller scale features (e.g. for the same roughness index spawning exhibits a smaller standard deviation than that of a flood event).

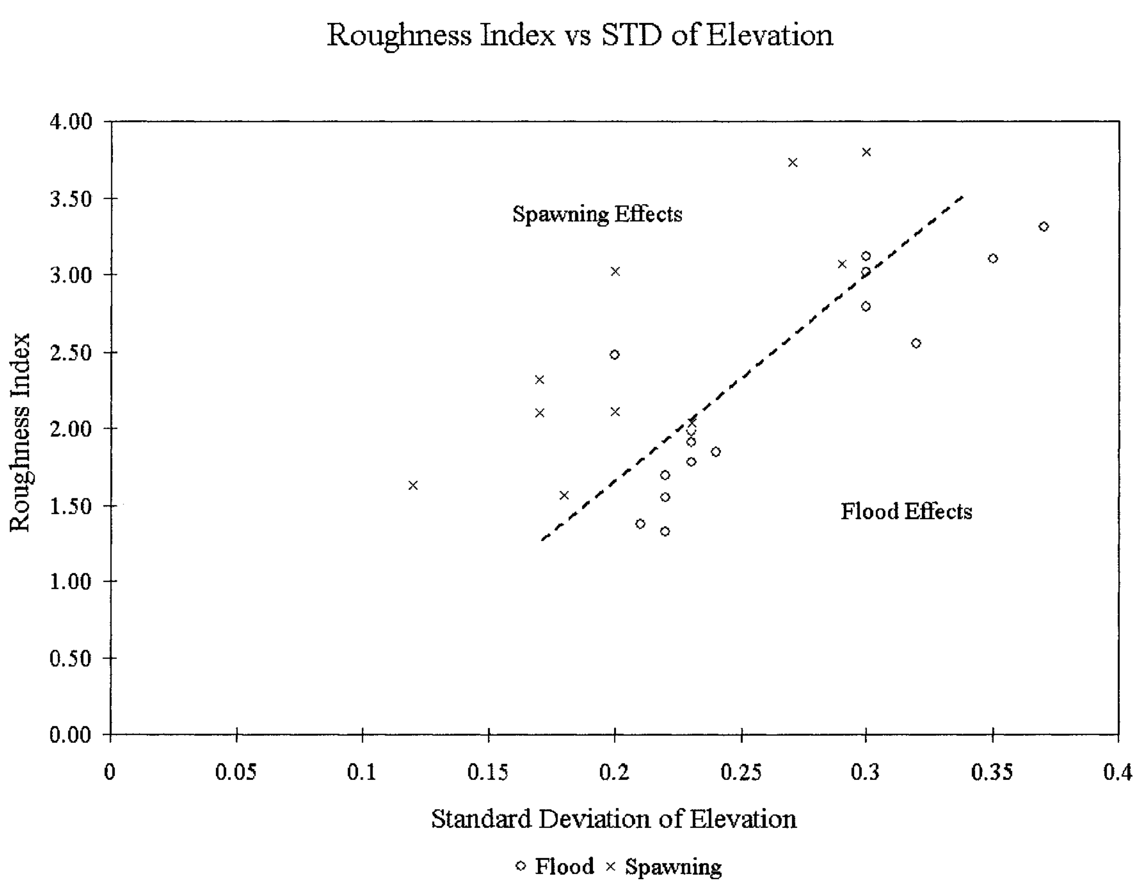

Figure 80: Standard Deviation of Elevation Versus Roughness Index

5.6 Effective depth of change

The nature of sediment transport in streams is such that the bed load transport rate is not solely dependent upon hydraulic parameters but also upon the interrelationship between bed material characteristics and flow properties (Gomez 1983). The problem is accentuated by the fact that buried particles are exposed and exposed particles are buried.

Hassan et al. (1994) define the "active layer" to be the layer of episodically mobilized material of the streambed. Numerous studies have suggested that bed load transport mostly takes place within an active layer, two clasts thick (Sutherland 1987, Carling et al. 1998). Mapping of the thickness of streambed changes permit examination of this concept.

Gravel particles in the streambed tend to align themselves with the A-axis perpendicular to the flow (Laronne and Carson 1976), the B-axis parallel to the flow and the C-axis perpendicular to the streambed. Since the C-axis is generally not truly vertical, the thickness of the gravel layer is a combination of the C-axis and a portion of the B-axis. The angle of the B-axis to the plane of the streambed is thought to average between 10 and 30 degrees. The thickness of the top clast layer on the streambed is dependent on the framework clast size at each locality. From Table 2, the average C-axis for Forfar 250 is 3.78 cm and the average B-axis is 5.21cm. An estimate of the average thickness of one clast thick for Forfar 250 stream section, using 10 degrees conservatively, would result in a thickness of 4.685cm (3.78 cm + 5.21 * Sin [10°]). To obtain the two clast thickness, the result of the calculations, using data from Table 2, were doubled resulting in two clast thickness (Table 16).

Event	2-Clast Thickness(cm)
Forfar 250	9.37
Forfar 1050	10.89
Forfar 1545	11.75
O'Ne-ell 925	9.78
O'Ne-ell 1550	10.66
Overall Average =	10.49

Table 16: Two Clast Thickness Values for Each Reach

The mean particle size increases with increasing stream gradient in both Forfar and O'Ne-ell Creek. Using the values of two clast thickness, the percent of volume change within two clast thickness was calculated for nival floods, summer floods and redd excavation (derived from data presented in Table 8,9,10) and are reported in Table 17.

	Forfar 250		Forfar 1050		Forfar 1545		O'Ne-ell 925		O'Ne-ell 1550		Average
Stream Gradient	0.50%		0.90%		1.70%		0.55%		0.50%		
2-Clast thick (cm)	9.37		10.89		11.75		9.78		10.66		
Study Year	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	
Nival flood											
Percent Fill within 10 cm =	33%	78%	60%	28%	39%	19%	14%	9%	25%	22%	
Percent Cut within 10 cm =	41%	9%	15%	44%	22%	43%	52%	63%	26%	22%	
Fill plus Cut within 10 cm =	74%	87%	75%	71%	61%	61%	67%	72%	51%	44%	66.3%
Zero Change	20%	6%	13%	12%	9%	8%	10%	12%	7%	6%	10.3%
Total	94%	93%	88%	83%	70%	70%	77%	83%	58%	50%	76.6%
Summer Flood											
Percent Fill within 10 cm =	53%		51%		21%		23%		25%		
Percent Cut within 10 cm =	22%		26%		24%		50%		18%		
Fill plus Cut within 10 cm =	75%		77%		45%		73%		42%		62.4%
Zero Change	15%		17%		6%		16%		5%		11.8%
Total	90%		93%		51%		89%		48%		74.2%
Redd Excavation											
Percent Fill within 10 cm =	17%	22%	35%	64%	35%	71%	25%	36%	20%	19%	
Percent Cut within 10 cm =	52%	49%	40%	13%	30%	3%	42%	37%	45%	40%	
Fill plus Cut within 10 cm =	69%	70%	75%	77%	65%	75%	67%	73%	64%	59%	69.4%
Zero Change	19%	23%	17%	18%	9%	14%	13%	21%	9%	8%	15.0%
Total	88%	93%	91%	95%	74%	89%	80%	93%	73%	67%	84.4%

Table 17: Summary Percentage for Depth for Change for 10 cm thickness

The range of volumes transported in a layer 2 clasts thick ranges between 50% and 94% for nival floods. For Forfar Creek, there seems to be a trend of decreasing two clast thickness with increasing stream gradient. The higher stream sections tend to have lower percentages of the stream bed modified to a depth equivalent to 2 clast thickness. The summer flood has a slightly lower average of two clast thickness change than that of nival flood. The redd excavation two clast thickness summary does not demonstrate any pattern with stream gradient and the percent volumes of change are very similar between each stream section.

The percent volumes of change are graphed by stream section and presented in Figure 81. The two processes under study have been separated. It is apparent that there is a downward trend in the volume of 2 clast thickness moved with increasing stream gradient. In general, the active layer of two clast thickness seems to be supported with the results from this thesis with an average percent volume of change of 75.4% for nival and summer floods. The redd excavation average percent volumes of change is 84.4% which is higher but similar in magnitude to floods.

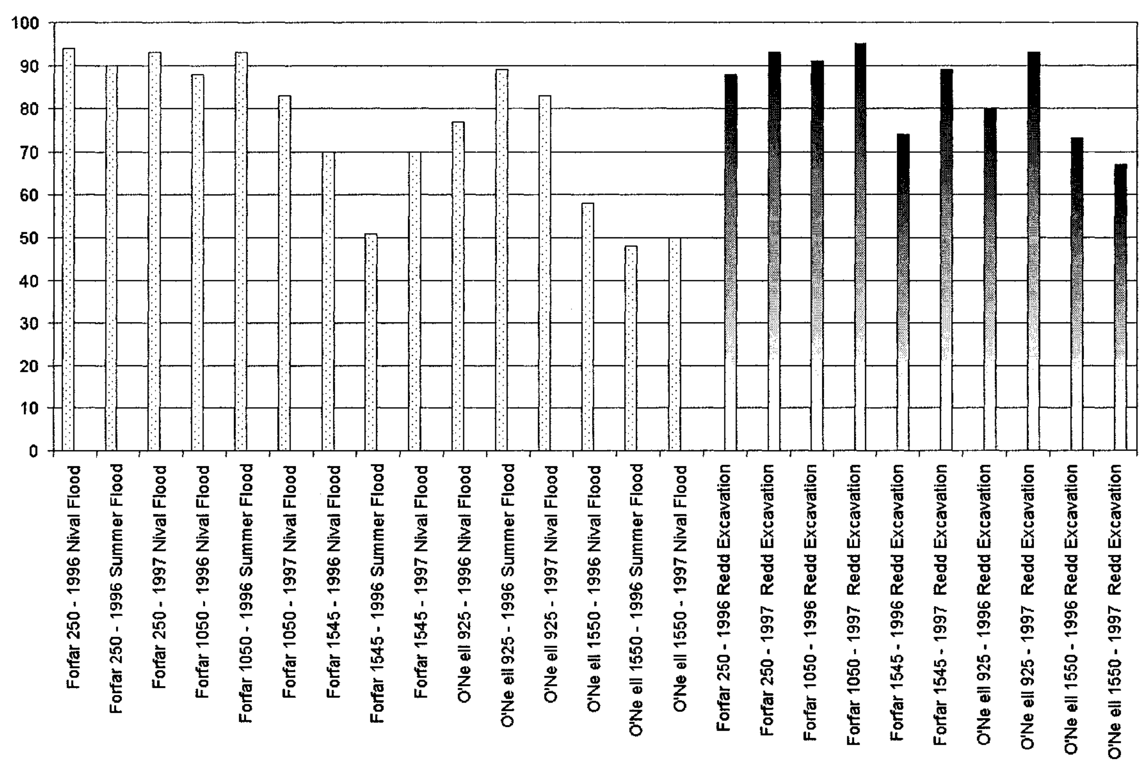

Figure 81: Flood and Redd Percentage Volume Moved within 2 Clast Thickness

Chapter Six

Conclusions

6.0 Conclusions

The intent of this study was to measure the magnitude of changes resulting from redd excavation of the streambed and compare them with flood related morphological change. The results demonstrated that the average magnitude of changes for floods (0.045 m^3/m^2) was very similar to that of the redd excavation events (0.034 m^3/ m^2). The streambed morphology following the spawning event dominates the stream topographical regime, persisting nine months of the year, from August to April. The nival or summer flood surface topography lasts for a period of one to three months, May to July, until the sockeye salmon returns to the stream.

Stream power predicts the depth of disturbance during floods (R^2= 0.73). The steeper stream sections in the study show a greater depth of change than lower gradient stream sections. Stream bed modification due to redd excavation is related to the number of females. The number of female sockeye salmon spawners plotted against the measured unit depth of change demonstrated a overall correlation for the two years of R^2=0 .48. The unexplained variability may be a function of spawning areas that have been excavated twice without a large increase in surface topographical change.

The erosional patterns of the hydrological and bioturbation processes were found to be very different. Flood related events tended to have a linear pattern of erosion with elongated surface features. The pools tended to be excavated while the riffles are aggraded. Redd excavation events produced a hummocky surface morphology over the streambed. The riffles and the side of the point bars tend to be excavated while the pools tend to be filled in. Due to low stream power during the sockeye salmon spawning event, the transported material stays in the pools until the stream discharge increases the following spring resulting from the snow melt event.

Redd excavation increases the roughness of the streambed. This is observed in seven out of the ten cases. The roughness of the stream surface slightly decreases between the fall of 1996 and the spring of 1997. Possible causes might be compaction of the gravel over the winter and/or the occurrence of fall rain flood events.

The concept of the active layer was addressed by comparing the volume of changes in the stream within a two clast thickness. The average change within two clast thickness was found to be 78% of the volume. It is interesting to note that the higher stream power sections have a lower percentage of change within two clasts even when correcting for the clast size. This might demonstrate that the concept of active layer is not solely proportional to the grain size distribution in the stream but also dependent on the gradient of the stream. Further work is required so that this hypothesis can be evaluated.

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